Institute of Physics Publishing
doi:10.1088/1742-6596/19/1/017

Journal of Physics: Conference Series **19** (2005) 97–101
Conference on Atoms and Molecules near Surfaces

Atomic quantum systems in optical micro-structures

T. Müther[1], J. Nes[1], A.-L. Gehrmann[1], M. Volk[1,2], W. Ertmer[1], G. Birkl[1,2], M. Gruber[3], and J. Jahns[3]

[1] Institut für Quantenoptik, Universität Hannover, Welfengarten 1, 30167 Hannover, Germany
[2] Institut für Angewandte Physik, Technische Universität Darmstadt, Schlossgartenstraße 7, 64289 Darmstadt, Germany
[3] Lehrgebiet Optische Nachrichtentechnik, FernUniversität Hagen, Universitätsstr. 27/PRG, 58084 Hagen, Germany

E-mail: `gerhard.birkl@physik.tu-darmstadt.de`

Abstract. We present experiments with cold atoms in optical dipole potentials which are directed towards developing an integrated coherent atom optics with micro-optical systems. We describe an experiment on evaporative cooling in a far-detuned optical dipole trap for ^{87}Rb. The dipole trap is created by a solid state laser at a wavelength of 1030 nm. To achieve high initial phase space densities allowing for efficient evaporative cooling, we have optimised the loading process from a magneto-optical trap into the dipole trap. Starting with an initial phase space density of 2×10^{-4} the trap depth was ramped down and temperatures below 200 nK and phase space densities of about 0.2 could be reached. These investigations aim at the creation of an 'all-optical' BEC based on a simple experimental scheme. As an example for an integrated atom optical system, we present the transport of atoms in a ring-shaped guiding structure, i.e. optical storage ring, for cold atoms which is produced by a micro-fabricated ring lens.

Since the first experimental observation of Bose-Einstein condensation (BEC) in 1995 [1] many groups have managed to achieve BEC by evaporative cooling in different magnetic trap configurations. Especially with microfabricated magnetic traps, so called 'atom chips', a large variety of trap geometries can be realised [2]. But, for some experiments magnetic traps have two important disadvantages: Firstly, not all atomic spin states can be trapped and secondly, a magnetic trap can not be used to examine the behaviour in homogeneous magnetic fields like it is required for the study of Feshbach resonances. Therefore, in these experiments the atoms are transfered from the magnetic trap into an optical dipole trap after the creation of the BEC. For some purposes it is advantageous to produce the Bose-Einstein condensate directly in the optical potential. With the use of microfabricated optical elements, it is in principle possible to reach a similar variety in the trap design as with atom chips [3].

So far several groups succeeded in reaching quantum degeneracy by evaporative cooling of ^{87}Rb-atoms in a CO_2-laser dipole trap [4, 5] or by combining several cooling methods with a YAG laser trap [6]. With other elements like Cesium [7] and Ytterbium [8] BEC was reached in an optical trap as well.

In the experiment presented here, we examine evaporative cooling of ^{87}Rb in a crossed dipole trap which is produced by a solid state laser with a wavelength of 1030 nm. This laser system is experimentally easier to handle than a CO_2-laser system, because the wavelength of 1030 nm allows the use of the same optical materials for the setup of the dipole trap as for the cooling and detection beams.

The key point for creating an all-optical BEC is to obtain a high initial particle density

© 2005 IOP Publishing Ltd

License: CC BY-NC-ND 3.0 Unported - Creative Commons,
Attribution, NonCommercial, NoDerivs
https://creativecommons.org/licenses/by-nc-nd/3.0/

allowing for efficient evaporative cooling. In experiments by Kinoshita et al. [6] a high initial phase space density in a solid state laser trap at a wavelength of 1060 nm could be reached by loading the atoms from a three-dimensional optical lattice, which was used to pre-cool the atoms, into a large and very shallow dipole trap. This dipole trap was then compressed while the laser power was ramped down and a BEC with 3.5×10^5 atoms was produced after 2.6 s of evaporation.

Our approach is to combine a solid state laser trap with the much simpler loading scheme of the CO_2-laser experiments. The dipole trap is loaded directly from a magneto-optical trap (MOT). To obtain a high particle number in the dipole trap, one has to make sure that light induced loss mechanisms due to the MOT light are reduced during the loading phase. Therefore, a correct choice of the parameters of the MOT light during the loading phase is crucial.

The starting point of our experiment is a ^{87}Rb MOT. The cooling beams consist of three orthogonal retroreflected beams, which are tuned 17 MHz below the $5S_{1/2} \rightarrow 5P_{3/2}$, F=2 → F'=3 transition of ^{87}Rb. An additional repumping beam tuned to the F=1 → F'=2 transition is overlapped with the cooling beams. The dipole trap laser is left on during the whole MOT and dipole trap loading time. The MOT is loaded from an atomic beam for about 10 s, reaching a particle number of several 10^8 atoms. Then the parameters of the MOT light are changed such, that an optimum transfer efficiency into the dipole trap can be obtained. To reduce the losses due to light induced collisions during the loading phase the intensity of the repumping laser has to be lowered, and the detuning of the cooling laser must be increased. In the experiment best results could be reached when the repumping laser intensity was reduced to about 30 μW/cm^2 and the cooling laser was detuned -50 MHz to the red of the $5S_{1/2} \rightarrow 5P_{3/2}$, F=2 → F'=3 transition, for a duration of about 60 ms. In order to pump the atoms into the F=1 hyperfine state the repumping laser is shuttered 1 ms before the cooling laser beams are switched off. At the same time, the magnetic field of the MOT coils is switched off.

The dipole trap beams are generated from a commercial solid state laser (ELS VersaDisk) which runs at a wavelength of 1030 nm. Both beams are linearly polarized and focused ($w_0 \approx 40\ \mu m$). To prevent interference of the beams, they intersect at an angle of 90° and are polarized perpendicularly to each other. Each beam has a maximum power of about 8 W.

The atoms in the dipole trap are observed with absorption imaging. After the loading stage the atoms are held in the dipole trap for at least 50 ms, to allow for the untrapped atoms to leave the detection region. Then the shadow of the atoms in the dipole trap is imaged onto a CCD camera. A typical absorption image of the crossed dipole trap is depicted on the left side of Fig. 1.

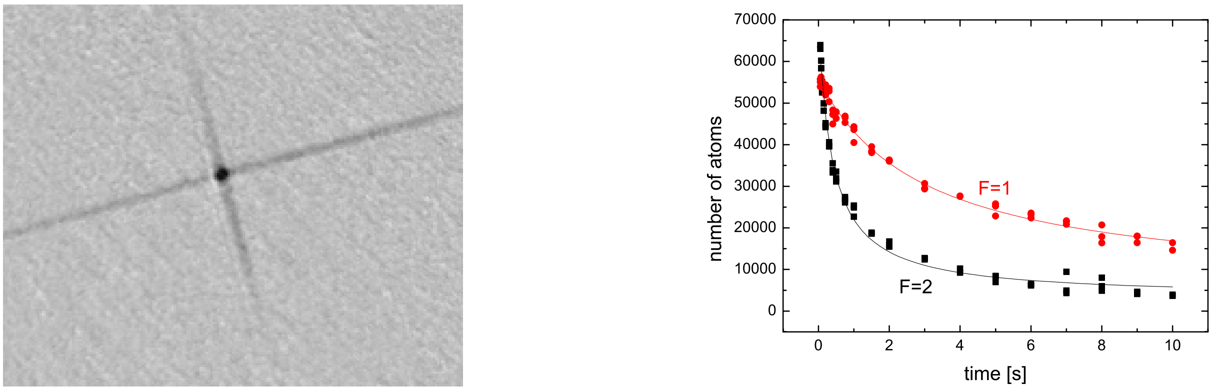

Figure 1. Absorption image of atoms in a crossed dipole trap (left). Lifetime measurement for atoms in the F=1 and F=2 hyperfine-substate of the $5S_{1/2}$-state (right).

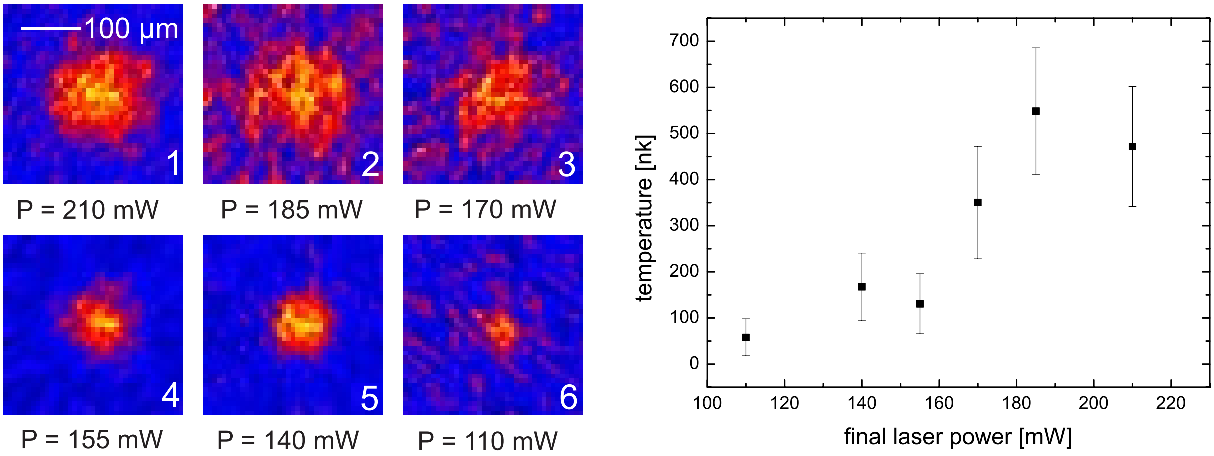

Figure 2. Absorption images after 10 ms TOF (left) and measured temperatures (right) for different values of the laser power at the end of the evaporation ramp.

For efficient evaporative cooling not only a high initial atom number is required, but also a high lifetime of the trap. In the right image of Fig. 1, the number of atoms in the trap was measured for different storage times. It can be seen that the lifetime for atoms in the F=1 state is much longer than in the F=2 state. Therefore, all further experiments were performed with atoms in the F=1 state. More detailed investigations of the data show that the lifetime of the trap is almost only limited by two-body losses. Losses due to trap-laser instabilities, near resonant scattered light, and background gas collisions can be neglected.

Forced evaporative cooling requires selectively removing the hottest atoms from the trap such that the remaining atoms rethermalize at a lower temperature. The easiest way to do this in an optical trap is to lower the trap depth by ramping down the laser power. This technique was first experimentally demonstrated by Adams et al. [9]. In this experiment, starting with an initial particle number of only 5000 atoms, an increase in phase space density by a factor of about 30 could be reached. This method is also used in our experiment. We start with a particle number of 60000 in the dipole trap. Considering the geometry of the trap and the temperature we get an initial value of 6×10^{-4} for $n\Lambda_{dB}$. Assuming that the atoms are equally distributed between the three m_F-substates of the F=1 state, this corresponds to an initial phase space density of 2×10^{-4}.

After the loading phase the atoms are held in the dipole trap for 100 ms to allow the hottest atoms to leave the trap ('self evaporation'). Then the trap laser power is reduced with the help of an acousto-optical modulator (AOM). The power is decreased with three linear ramps over a time of 2.5 s from a total Power of 16 W in both beams to an end value between 210 mW and 110 mW, corresponding to trap depths between $k_B{\times}10\ \mu K$ and $k_B{\times}5\ \mu K$, if the influence of gravity is neglected. With this method, temperatures below 200 nK can be reached. In Fig. 2, absorption images after 10 ms time of flight (TOF) are depicted. One can see that the clouds, and thus the temperatures, become considerably smaller for smaller trap depths. More detailed analysis of the images show that phase space densities of about 0.2 are reached in images 4 and 5. In image 6 one can see a strong decrease in the particle number compared to the images 4 and 5. This is due to the fact that at low trap laser power the atoms fall out of the trap. For even lower laser powers, gravity exceeds the dipole force and no atoms can be held in the trap any more.

A crossed dipole trap, like the one used for the evaporation experiments, has a relatively simple trap geometry. By using microfabricated optical elements, one can create a wide variety

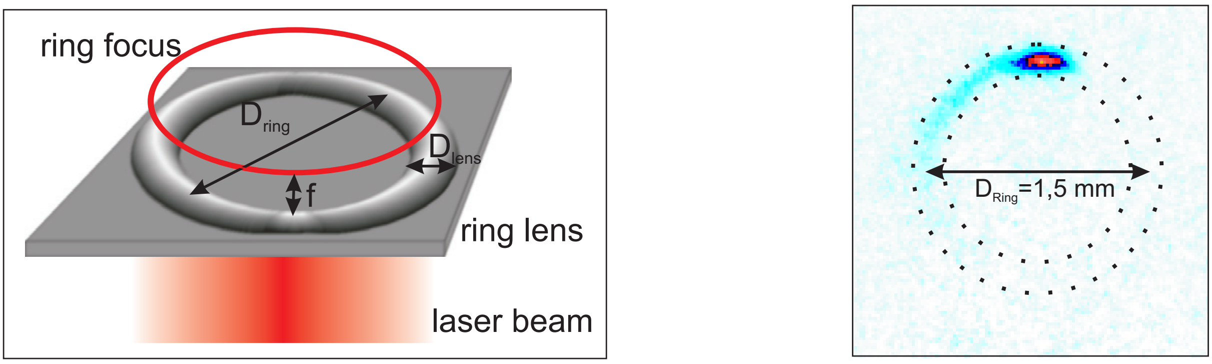

Figure 3. Schematic of the ring lens (left) and fluorescence image of the atoms in the storage ring (right).

of more complex trapping and guiding structures for cold atoms [3]. So far, microfabricated optical elements have been used to create arrays of microtraps [10] and interferometric guiding structures [11]. Here, we present first results of a next-generation experiment for guiding of atoms: an all-optical storage ring based on a cylindrical ring lens. The ring lens was designed and lithographically fabricated in collaboration with the group of Prof. Jahns at the FernUniversität Hagen.

The image on the right side of Fig. 3 is a fluorescence image of atoms which are trapped in a ring focus. To obtain this, a ring lens with a diameter of the ring of D_{ring}=1.5 mm was illuminated with light of a Titanium-Sapphire laser, running at a wavelength of 780.7 nm, and the focus was imaged into the MOT, such that the upper part of the ring focus was overlapping with the MOT. Then the MOT was switched off to let the untrapped atoms leave the detection region. The remaining atoms propagate in the ring structure. For a homogeneously illuminated ring, the atoms would move due to the influence of gravity to the bottom of the ring. Because of the large area of the ring and limited laser power, it was not possible to illuminate the whole ring in such a way to obtain a sufficient trap depth all over the ring. Therefore, only part of the ring lens was illuminated and the atoms are guided in circular arc structure of length of a quarter of the ring circumference.

The observed increase in phase space density of a factor of 1000 in the evaporative cooling experiment gives hope that after further improvement of the loading process, it should be possible to reach an all-optical BEC in a crossed dipole trap at 1030 nm directly loaded from a MOT. The BEC can then be loaded into an optical storage ring like the one presented here. Due to the much lower temperatures of the quantum degenerated ensemble, a much lower trap depth, and thus less laser power is required for holding the atoms in the ring. Because of its enclosed area, the ring structure can be used as a guided atom interferometer and matter-wave resonator for the study of the coherence properties of the trapped BEC.

References

[1] M.H. Anderson et al. 1995 *Science* **269**, 198; K.B. Davis et al. 1995 *Phys. Rev. Lett.* **75**, 3969; C.C. Bradley et al. 1995*Phys. Rev. Lett.* **75**, 1687.

[2] H. Ott et al. 2001 *Phys. Rev. Lett.* **87**, 230401; W. Hänsel et al. 2001 *Nature (London)* **413**, 498; S. Schneider et al. 2003 *Phys. Rev. A* **67**, 023612.

[3] G. Birkl, F.B.J. Buchkremer, R. Dumke, and W. Ertmer 2001 *Opt. Comm.* **191**, 67.

[4] M.D. Barret, J.A. Sauer, and M.S. Chapman 2001 *Phys. Rev. Lett.* **87**, 010404.

[5] G. Cennini, G. Ritt, C. Geckeler, and M. Weitz 2003 *Appl. Phys. B* **77**, 773, *Phys. Rev. Lett.* **91**, 240408.

[6] T. Kinoshita, T. Wenger, and D.S. Weiss 2005 *Phys. Rev. A* **71**, 011602.

[7] T. Weber, G. Herbig, M. Mark, H.C. Nägerl, and R. Grimm 2003 *Science* **299**, 232.

[8] Y. Takasu et al. 2003 *Phys. Rev. Lett.* **91**, 040404.

[9] C.S. Adams, H.J. Lee, N. Davidson, M. Kasevich, and S. Chu 1995 *Phys. Rev. Lett.* **74**, 3577.

[10] R. Dumke, M. Volk, T. Müther, G. Birkl, and W. Ertmer 2002 *Phys. Rev. Lett.* **89**, 097903.

[11] R. Dumke, T. Müther, M. Volk, W. Ertmer, and G. Birkl 2002 *Phys. Rev. Lett.* **89**, 220402.