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A versatile all-optical Bose–Einstein condensates apparatus

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We report on the construction of an all-optical Bose–Einstein condensate apparatus by using a CO2 laser trap. We also report on measurements of the trap frequency by applying a periodic perturbation to the trap potential. The derived trap parameters agree well with the design parameters. © 2008 American Institute of Physics. [DOI: 10.1063/1.2917405]

I. INTRODUCTION

Since the first achievement of a Bose–Einstein condensate (BEC) in a weakly interacting gas,1–3 the study of BECs has become an extremely active field of research. Several review articles4,5 and books6,7 have been written on recent exploits. By far, the majority of BEC experiments use magnetic confinement of the atoms. This traps atoms in a specific magnetic substate (the “weak field seeking” state). Evaporation in these experiments is forced by inducing a rf transition between the weak field seeking and “strong field seeking” states at a particular magnetic field. The strong field seeking atoms are accelerated out of the trap by the magnetic field.

A different way to produce a BEC is to use an optical trap, formed by the focus of a strong laser. Unlike a magnetic trap, such a laser trap captures all atoms, regardless of their electronic state, and hence there is no way to evaporate atoms by inducing transitions to an “untrapped” state. Hence, evaporation is forced by lowering the laser power, allowing the hotter atoms to escape. However, this means that the spring constant of the trap is also reduced as the laser power is reduced, which means that the density decreases. This leads to a different evaporation sequence than typical for a magnetic trap. Such an “all-optical” BEC was first reported by Barrett et al.,8 and has since then been reported by other groups.9–13 The advantage of trapping all states is that experiments can be performed on any atomic state in the trap. This can potentially be used for the study of spinor condensates,14–16 or to encode quantum information in the electronic states of the atom. The CO2 laser trap can be operated in a standing wave configuration, allowing such experiments by using arrays of traps, and hence multiple atomic samples.17 Furthermore, the laser intensity can be changed on a time-scale smaller than 1 μs, allowing for detailed studies of the dynamics of the condensate.

Here, we report on the construction and present some diagnostic results obtained from the study of such an all-optical BEC. After the BEC is formed, the trapping potential is perturbed by modulating the trap laser intensity. This gives rise to a periodic, spatially symmetrical distortion of the trapping potential. If the modulation frequency is resonant with the corresponding trap frequency, this would give rise to an excitation of a breathing mode. Such periodic modulation has been widely used5 to establish the value of the trap frequency.

II. VACUUM SETUP

We use a dual MOT system18 by using two separate stainless steel vacuum chambers. We use a filament (SAES getters) to create a vapor pressure in the initial magneto-optical trap (MOT) chamber of ~10−8 mbar. The initial MOT is a conventional six-beam setup. Every 100 ms, the atoms in the initial MOT are pushed by a 10 ms radiation pressure pulse to a secondary MOT chamber through 100 mm long and 8 mm φ tube, which acts as a vacuum separation. We load about 1010 87Rb atoms into the secondary MOT, with a cloud diameter of ~3 mm in about 30 s.

The secondary MOT vacuum chamber is relatively large and is constructed from two 12 in. conflat flanges, spaced by a 75 mm long, 250 mm diameter tube, as illustrated in Fig. 1. Additional windows are mounted on this basic structure as detailed below. The chamber allows for in-vacuum mounting of optics, such as the focusing lenses for the CO2 laser beams and high-finesse cavities or particle detectors. At present, a channeltron electron multiplier is mounted in the vacuum system. Furthermore, the vacuum chamber has been designed for optimal optical access in as many dimensions as possible. Also, a larger chamber allowed for many windows, which are anti-reflection (AR) coated and perpendicular to the laser beams, thereby reducing the amount of stray light in the chamber. The crossed CO2 laser beams are in the horizontal plane and enter under 45° with the chamber axis. The MOT laser beams all enter under 50° with the horizontal plane. 60 mm φ viewports (4 1/2 in. conflat), mounted at a distance of 100 mm from the trap, provide large numerical aperture views from the top and the bottom of the chamber. Furthermore, two axes in the horizontal plane provide access for additional experimental laser beams. This vacuum chamber is pumped by an ion pump and a Ti sublimation pump. These pumps are mounted to a third vacuum chamber, in line with the first two. The connection between the second MOT and third vacuum chamber is formed by a 62 mm diameter, 200 mm long tube. The resulting background pressure in the secondary MOT is <10−11 mbar. The corresponding lifetimes of the secondary MOT are in the order of 2 min.

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**References**


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**Author Notes**

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As seen in Fig. 1, the (horizontal) axis of symmetry of the quadrupole magnetic field for the secondary MOT does not have a laser beam on it, as is the case in a classical six-beam MOT. It was found that the MOT works equally well in this arrangement, and it simplifies future experiments, allowing free access to a horizontal pair of viewports.

### III. DIODE LASER SYSTEMS

The primary MOT laser is set up by using a master-slave arrangement. A home-built external cavity laser using the Sanyo DL7140-201 acts as the master laser, using the Hänsch design.\(^{19}\) It is stabilized to the \(F=2\rightarrow F’\) multiplet using a standard saturated absorption arrangement. The output power of this laser is about 20 mW. Half the output of this laser is injected into a free-running Sharp GH0781RA2C diode laser, which acts as the slave. The output of this laser system is 55 mW, which is sufficient to run the primary MOT. The output of the slave laser is double passed through an 80 MHz acousto-optical modulator (AOM), which allows fast switching, and is passed through a shutter to allow it to be completely extinguished, before being expanded and divided for a regular six-beam MOT.

The secondary MOT laser is a Toptica DLX 110. It is stabilized to the \(F=2\rightarrow F=3\) transition by using a polarization spectroscopy scheme.\(^{20}\) This scheme yields an excellent steep slope for stabilization, allowing a higher bandwidth for the lock loop. However, as this scheme is sensitive to optically pumping the atoms to a stretched magnetic substate, this scheme can only lock on the two-level resonance. As the primary laser beam needs to be double passed through an AOM for fast switching and frequency tuning, this means that the stabilization beam needs to be double passed through an AOM before entering the polarization spectroscopy setup to cancel the frequency shift. The primary beam is furthermore passed through a shutter and a polarization preserving fiber before entering the vacuum chamber.

The imaging and push laser beams are also derived from the Toptica laser and are both double passed through an AOM. The imaging laser is passed through a single mode polarization preserving fiber before entering the vacuum chamber from the top. The push laser beam has a \(\sim 50 \mu m\) focus on the primary MOT, and consequently the intensity of this laser beam has significantly decreased at the secondary MOT, thereby minimizing disturbance of the second MOT by the push laser.

### IV. DIPOLE TRAP

The secondary MOT is overlapped by a dipole trap, which is formed by a crossed pair of CO\(_2\) laser beams, with waist radii \((1/e^2)\) \(w_0 = 40 \mu m\). The CO\(_2\) laser is a Coherent GEM-25 water cooled multimode laser. The beam is horizontally polarized and has an initial diameter of 1.8 mm and a divergence of 7.5 mrad. The beam is passed through an AOM for intensity control, before being expanded using a 4.5× beam expander to yield an \(\sim 20 \text{ mm}\) diameter beam and split in 50/50 by using a nonpolarizing beam splitter (Wavelength Technology Singapore P/N BS2-2-5-50-I). The beams enter the vacuum chamber through AR coated ZnSe windows mounted on CF flanges (Insulator Seal Incorporated P/N 9792901). In the vacuum chamber, the beams are focused by aspheric lenses \((f=55 \text{ mm}, \text{II-VI Incorporated P/N 684500})\) and recollimated after the focus by another set of \(f=55 \text{ mm}\) lenses before exiting the chamber through another set of ZnSe windows. The beams subsequently run into beam stops. Great care is taken that all CO\(_2\) laser optics is AR coated and that reflections from optical surfaces do not leave the optical table. In Fig. 2, we show a bird’s eye view of the CO\(_2\) laser trap setup. Note that the polarization of the laser beams is in the plane of the drawing, thereby (largely) avoiding interference between the laser beams.

The power in each of the CO\(_2\) laser beams is initially 10 W. The laser power can be varied by controlling the amplitude of the rf drive to the AOM. The CO\(_2\) laser wave-
length is 10.6 μm, very far red detuned from all allowed ground state transitions. Hence, the shift of the energy levels is determined by the dc polarizability of the levels. The dc polarizability of the ground state of rubidium αg = 5.3 \times 10^{-39} \text{m}^2 \text{C/V}. With our laser beam parameters, this translates to a trap depth for the ground state atoms in trap of \( -0.5 \text{ mK} \) and trap frequencies of 2.6 kHz (vertically) and 1.9 kHz (horizontally).

V. EXPERIMENT CONTROL

The experiment is controlled by using a personal computer running Linux with the RTAI extension.21 An Eagle PCI-703 multi-io card and an Eagle PCI-766 DAC card provide the necessary output voltages, analog inputs, and digital bits to control all AOMs and shutters. The RTAI Linux, using the LXRT mechanism, yields a timing jitter of about 5 μs, adequate for our needs, although RTAI is capable of performing more accurate timing by using different mechanisms. The experiment control program is written in C++ by using Qt to build the graphical user interface.

The images are collected by using a Princeton Instruments (PI) Photonmax charge coupled device (CCD) camera, using the Linux drivers and data acquisition library from PI. The Qt library allows easy visualization of the images, and the images are subsequently stored in the FITS data format. This data format allows multiple images, along with all the experimental settings, to be stored in a single data file, which can be read by MATLAB and many other third-party image processing software packages.

VI. BEC SEQUENCE

In an all-optical trap, the geometry of the trap is fixed, and hence to efficiently load atoms from the MOT into the dipole trap, a high density is desirable. This can be achieved by reducing the photon scattering rate of the atoms in the MOT, while keeping them trapped.24 To achieve such a smaller scattering rate, we reduce the repump power in the MOT from 1 mW to 1 μW for 200 ms, while at the same time, the detuning of the MOT laser is increased to –40 MHz. The small repump power allows the atoms to spend a large fraction of the time in the \( F=\pm 1 \) state, where they cannot be excited by the trap laser. The reduced excited state population reduces the interaction between the atoms, thereby allowing a larger density.

Subsequently, the detuning of the MOT laser is increased to –160 MHz for 40 ms, yielding efficient loading of the dipole trap in the \( F=1 \) state. This large detuning is achieved by using the zeroth order of the (double pass) 80 MHz AOM as the cooling light.

As mentioned earlier, evaporative cooling is achieved by lowering the laser power. The CO2 laser power is ramped from 10 W down to 1 W per beam in 1 s, and subsequently from there to 150 mW per beam in 2.5 s, and finally from there to 40 mW per beam in 5 s. This forces evaporative cooling of the atoms down to BEC at a transition temperature of 50 nK.

By completely extinguishing the CO2 laser, the atoms are allowed to expand for 10 ms and subsequently optically pumped to the \( F=2 \) state before detection by flashing on the MOT repump laser for 200 μs. We detect the atoms by using on-resonance absorption of a probe laser beam on the \( F=2 \rightarrow F=3 \) transition. The imaging laser pulse has a duration of 100 μs and an intensity equal to the saturation intensity of the transition. It is directed perpendicular to the plane of the drawing in Fig. 2, and hence the images represent column densities in the plane of the drawing. We construct a 1:1 image of this on the CCD camera by using an aspheric \( f=11 \text{ mm} \) lens. We will refer to this image as a. Hence, one pixel on the CCD camera (25 μm) translates to 1.84 μm in the trap.

To obtain the absorption image, a second image is taken 1 s later with an identical laser pulse (b), and a third image is obtained without any laser light to obtain a background reading (c). The absorbed fraction \( F \) is then obtained from \( F = (b-a)/(b-c) \), and this is what is plotted. The transmitted fraction \( t = 1 - F \) can be related to the number of atoms \( N = \sum_{\text{pixels}} - (A/\sigma) \ln(t) \), where \( A = 3.4 \times 10^{-13} \text{ m}^2 \) is the area of one pixel and the photon absorption cross section \( \sigma = 1.3 \times 10^{-13} \text{ m}^2 \).

In Fig. 3, we show an absorption image of a thermal cloud of atoms just above the transition to BEC (left), one of a partially condensed cloud (center) and one of a fully condensed cloud (right). Note the onset of an asymmetric velocity distribution as the cloud traverses the critical temperature. This velocity distribution reflects the detailed shape of the trap, which is asymmetric due to residual interference effects between the laser beams. The number of atoms in the condensate is found to be \( \sim 10^4 \).

VII. TRAP FREQUENCY MEASUREMENTS

We now investigate the excitation spectrum of the atoms in the BEC by modulating the CO2 laser power. The laser intensity distribution for a pair of crossed Gaussian laser beams with total power \( P \) per beam is to good approximation given by

\[
I(x,y,z) = \frac{2P}{\pi w_0^2} [e^{-2(x^2+y^2)/w_0^2} + e^{-2(z^2+y^2)/w_0^2}]
\]

with \( w_0 \) the beam waist size, giving rise to the potential,
with \( c \) is the speed of light in vacuum, \( e_0 \) is the electric permeability, and \( m \) is the mass of a rubidium atom (87 amu). It is trivial to show that the horizontal trap frequency \( \omega_h \) scales with the laser power \( P \) in one of the beams as

\[
\omega_h = \sqrt{\frac{2P\alpha_c}{\pi w_0^4 e_0 m}}.
\]

In the vertical direction, gravity needs to be taken into account, evaluating the trap potential. At low trap laser powers, the trap sags under gravity. The vertical position of the trap minimum is now given by

\[
z_0 = \frac{1}{2} \sqrt{-w_0^2 V(0) - m^2 g^2 w_0^2 \pi^2 c^2 e_0^2 \frac{1}{64 P^2 \alpha_c^2}}.
\]

When the trap depth is modulated at a frequency near a trap frequency, it is likely that the atoms are excited to a higher trap state and out of the condensate. In the horizontal direction, the trap is symmetrically deformed, and hence we would expect the excitation of a quadrupole, “breathing” mode of the condensate. This means we would expect a resonance at \( 2\omega_h \). However, in the vertical direction, \( z_0 \) is modified as the laser power is changed, and hence we would expect to be able to excite a dipole, “sloshing” excitation at \( \omega_z \).

We investigate this behavior by slowly (0.1 mW/ms) raising trap depth to an adjustable level, and subsequently applying a small modulation (3% of the offset power) at an adjustable frequency on the trap laser power for 500 ms. We then image the velocity distribution of the atoms by the absorption technique discussed before. In Fig. 4, we show a series of absorption images of the atoms for different modulation frequencies at an offset power of 100 mW. Clearly visible is that a modulation frequency of 130 Hz, the atoms are heated up much more than at frequencies that are higher or lower than this resonant frequency.

We then vary the offset power of the CO\(_2\) laser and take a series of measurements with varying modulation frequencies. At each offset power, there is a clear resonant frequency. The resonant frequency as a function of offset power is displayed in Fig. 5, with the measured resonance frequency represented by the circles. The line in the figure is represented by a fit of Eq. (5) to the data, where the waist size \( w_0 \) and a multiplication factor for the laser power are free parameters, yielding an excellent fit to the data. The fitted waist radius is \( w_0 = 40.7 \pm 2.3 \mu m \), in good agreement with the design parameters.

**VIII. CONCLUSIONS**

In summary, we report on the all-optical creation of a BEC in a dipole trap, formed by a crossed pair of CO\(_2\) laser beams. By performing spectroscopy on the trap frequencies, we determine the beam waist radius of the CO\(_2\) laser beams to be \( \sim 40 \mu m \). We discuss some application experiments of the all-optical BEC, which are much more difficult to access using a magnetic trap.
