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Laser cooling in a CO_2-laser optical lattice

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Abstract. We report on the trapping of laser-cooled rubidium atoms in the antinodes of an infrared standing wave near 10.6 μm. Intriguing properties of the resulting optical lattice are long coherence times and a large lattice period. We have experimentally verified the localization of the atoms in the antinodes of the standing wave field by measurement of the vibrational spectrum of the atoms. The phase-space density of the trapped atoms, cooled by optical means only, is less than three orders of magnitude below the threshold of Bose–Einstein condensation.

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Standing wave laser fields produce a periodic potential for atoms, which can trap cold atoms in an ordered crystal-like structure [1]. Such arrays of atoms in microscopic traps, named optical lattices, have attracted much research interest in recent years. Whereas in most optical lattices studied so far the light is tuned comparatively close to an atomic resonance, the optical lattice reported here is based on the light of a CO_2 laser near 10.6 μm detuned extremely far from the atomic resonances. We have successfully trapped laser-cooled rubidium atoms in the antinodes of a standing wave near 10.6 μm. This represents the realization of an optical lattice with a very large lattice period, being approximately 13 times that of the excitation wavelength of the lowest electronic resonance. Whereas in conventional optical lattices only a few percent of the lattice sites are occupied, in a future three-dimensional CO_2-laser lattice more than one atom per microscopic trap could be captured at moderate average atomic densities. Perhaps even more important, our lattice allows extremely long coherence times. In a first Rapid Communication, we recently described the first observation of atoms trapped in the antinodes of a CO_2-laser standing wave [2]. Besides describing that work more in detail, we here report on recent progress in our experiment. We now have reached a phase-space density of the trapped atoms – cooled with optical techniques only – of more than three orders of magnitude above that of a magnetooptical trap, and less than three orders of magnitude away from Bose–Einstein condensation. So far, we still make use of simple laser-cooling techniques based on the MOT beams. Before describing our experimental work [2, 3], we want to give a more general account of the motivations for our research on these novel optical lattices.

1 Atomic sources with high phase-space densities

In recent years we have witnessed much progress in the preparation of cold atomic sources by means of laser cooling [4]. However, since the cooled atoms are emitted incoherently, such sources still resemble an ordinary lamp. Similarly as the availability of the laser as a coherent source of photons has revolutionized the field of light optics, coherent sources of atoms are expected to find intriguing applications in atom optics. When an atomic gas is cooled to a sufficiently low temperature such that the thermal atomic de Broglie wavelength λ_{dB} exceeds the mean interatomic separation, one expects quantum statistical effects to occur [5]. The phase-space density $n\lambda_{dB}^3$ then exceeds unity. This situation has recently been achieved in several outstanding experiments with dilute atomic gases by means of evaporative cooling in magnetic traps, where laser cooling was used for precooling the atoms only [6, 7]. At very low, but finite, temperatures Bose–Einstein condensation of integer-spin atoms into the ground state of a trap has been observed. It has recently been proposed to reach an accumulation of atoms in the ground state of translational motion also in a nonequilibrium situation to form an "atom laser", which would be the matter wave analog to an optical laser for photons [8]. If atoms could be cooled into the quantum-degenerate regime by use of laser cooling only, one would not be limited to the generation of thermal distributions. Further, while evaporative cooling necessarily implies the loss of atoms, laser cooling could in principle work without losses.

With laser cooling in near-resonant light fields, as for example in a magnetooptical trap, one routinely reaches atomic temperatures in the μK regime (for heavy alkaline atoms) and densities up to about 10^{11} cm^{-3}, corresponding to an atomic phase-space density of 10^{-6} to 10^{-5}. The main density limiting processes, which are especially severe for large

light traps, are reabsorption of fluorescence photons, absorption of the trapping light beams, and collisions of excited state atoms [9]. Considerably higher atomic densities have been achieved in far-detuned optical dipole traps. Research groups in Stanford and Paris have obtained atomic phase-space densities up to almost 10^{-2} by Raman cooling in dipole traps [10, 11]. Similarly high phase-space densities have later been achieved in Paris with a simpler experimental setup by means of blue-detuned Sisyphus cooling in a dipole trap [12]. The trapping of atoms can now be achieved with light detuned extremely far from the atomic resonances, leading to dipole traps with low spontaneous scattering rate losses [10–13].

Laser cooling in traps is not only investigated experimentally with neutral atoms, but also very successfully with atomic ions in Paul traps [14]. Here the strong Coulomb interaction of the charged particles allows the realization of very steep traps with vibrational frequencies above the photon recoil energy, such that the Lamb–Dicke limit is fulfilled. By use of sideband cooling single ions have already been laser-cooled into the ground state of a trap [15, 16]. The strong Coulomb repulsion of the ions however inhibits the cooling of many ions into a single quantum state.

A further system where the cooling of single particles into the ground state of a trap with large probability has been achieved are optical lattices. The trapping potential for the atoms is determined by the ac-Stark shift due to the light–atom interaction and has the periodicity of the optical standing wave. In near-resonant optical lattices a Sisyphus cooling mechanism accumulates a large fraction of the atoms (up to 10 percent in the three-dimensional case) in the vibrational ground state. Since the atoms are localized to a fraction of a wavelength, the Lamb–Dicke condition is usually fulfilled. Recently, successful sideband cooling of atoms in an optical lattice has been reported in one and two dimensions [17, 18], and the possibility to extend these schemes to three-dimensional cooling has been anticipated.

If many atoms could be trapped at a single lattice site, there would be good prospects to reach the quantum statistical regime with more than a single atom population per quantum state by the use of laser cooling only. The mean population probability per lattice site in three-dimensional lattices is of the order $n(\lambda/2)^3$, with n as the average atomic density. In previous experiments typically only 5% of the lattice sites were occupied, since the mean atomic density in near-resonant optical lattices is limited to about 10^{11} cm^{-3}. An even more important problem of near-resonant light fields is the limitation of the coherence time by photon scattering. The photon scattering rate can be reduced by increasing the laser detuning from the atomic resonance. Several experiments with detunings around some nm have been reported, which lead to coherence times in the ms regime. In most of these earlier experiments the lattice constant was very close to that of the resonant standing wave.

In our work [2, 3] we investigate an optical lattice, where the trapping potential is formed by a standing wave near 10.6 μm. Although the light is detuned extremely far from the lowest electronic resonance of the rubidium atom near 795 nm, the dipole force still forms a steep trapping potential. With an expected average spontaneous photon scattering time of 20 min [13], extremely long atomic coherence times are possible. The lattice constant of our optical lattice is more than an order of magnitude above that of near-resonant optical lattices. Due to the comparatively large size of the unit cell, in a three-dimensional setup more than one atom per site can be trapped at the average atomic density of an ordinary magneto-optical trap. We note that more recently an optical lattice with periodicity much above an optical wavelength has also been realized – with however closer resonant light – by imaging of a phase grating [12].

2 Microscopic CO_2-laser dipole traps

Both ordinary dipole traps and optical lattices are based on the interaction of an induced atomic dipole moment with an off-resonant laser field. The light shift induced by an intense laser beam can lead to a noticeable change of the potential energy of an atom. When the laser frequency is tuned to the red side of an atomic transition, atoms are attracted towards the maximum of the field intensity. The trapping potential for atoms is $V = -1/2\alpha E^2$, where α denotes the atomic polarizability and E the amplitude of the laser field. Since the frequency of the CO_2 laser used in our experiment is approximately one order of magnitude below that of typical electric dipole transitions of ground state alkaline atoms, the forward and backward rotating wave contribute to the trapping potential by almost equal amounts. The atomic polarizability can therefore in good approximation be replaced by its static value α_s. For the ground state and the first excited state of the rubidium atom the scalar static polarizability is $\alpha_{5S} = 5.3(1) \times 10^{-39}$ m^{2}C/V and $\alpha_{5P} = 1.3(1) \times 10^{-38}$ m^{2}C/V [20]. Note, that both atoms in ground and excited state are trapped in the field maxima, while for near-resonant red-detuned optical fields – where a two-level approximation is valid – excited state atoms are pulled towards the field minima and can leave the trap.

The calculated potential depth for rubidium ground state atoms in the field maxima of a standing wave near 10.6 μm is 360 μK for 5 W light power and a 100-μm beam diameter. This trap depth is significantly higher than the atomic temperatures of a few μK obtainable by polarization gradient cooling, such that the cold atoms can be trapped in the antinodes. Figure 1 shows the light-shift potential for both ground

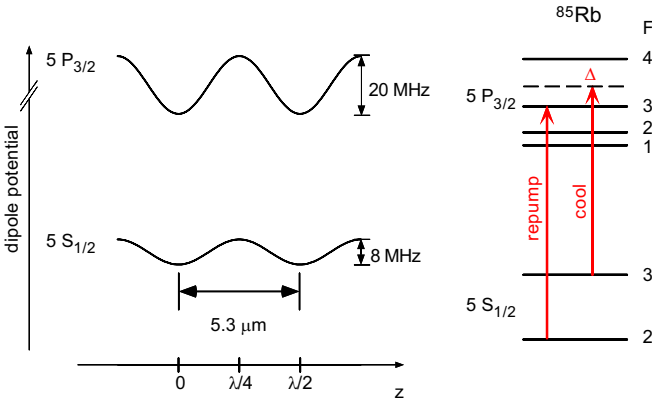

Fig. 1. (*Left*) Light-shifted potential of the $5S_{1/2}$ ground state and of the $5P_{3/2}$ excited state of the rubidium atom in a standing wave near 10.6 μm. The numeric values for the potential depth induced by the static (scalar) polarizability are given for 5 W of infrared power and a 100 μm beam diameter. (*Right*) Level scheme of the D2-line of the ^{85}Rb isotope including the hyperfine substates

and excited atomic states in an infrared standing wave with the quoted experimental parameters, resulting in a potential spatial periodicity of 5.3 μm. Novel laser cooling mechanisms can be envisioned, since the exited state is trapped more tightly than the ground state.

3 Experimental setup and procedure

A scheme of our experimental setup is shown in Fig. 2. Inside a vacuum chamber, rubidium atoms first are loaded from the background vapor into a magnetooptical trap. The cooling beams are provided by a grating-stabilized diode laser locked approximately four natural linewidths ($\Delta_1 = 4\Gamma$) to the red of the $5S_{1/2}$ ($F = 3$) to $5P_{3/2}$ ($F' = 4$) transition of the ^{85}Rb isotope. Optical pumping into the $F = 2$ ground state is prevented by irradiating the atoms with light from a second diode laser locked to the rubidium $5S_{1/2}$ ($F = 2$) to $5P_{3/2}$ ($F' = 3$) transition. During a typical MOT loading period of 3 s, a cold dense sample of typically 10^6 rubidium atoms is prepared. During the final 30 ms of the loading time the intensity of the repumping laser is reduced to 1/10 of its initial value, and the detuning of the MOT beams is shifted to a value of typically $\Delta_2 = 18\Gamma$ red of the cycling transition. Since the hyperfine splitting between the $F' = 3$ and the $F' = 4$ sublevel of the $5P_{3/2}$ exited state is 121 MHz corresponding to about 21 natural linewidths, the cooling laser by this time is blue-detuned with respect to the $5S_{1/2}$ ($F = 3$) to $5P_{3/2}$ ($F' = 3$) transition by about 3 natural linewidths. We thus expect both transitions to contribute to the laser cooling mechanism in this final cooling stage, yielding a combined red and blue Sisyphus cooling mechanism [21]. Due to the reduced repumping intensity yielding a temporal dark MOT the atoms spend most of the time in the lower ($F = 2$) hyperfine state and interact only very weakly with the cooling light, such that repulsive light forces between the atoms are reduced and the density increases [22].

To allow the trapping of the cold atoms in a dipole potential almost free of dissipation, we use a single-mode CO_2 laser delivering 10 W output power near 10.6 μm. The CO_2-laser beam enters the vacuum chamber through a ZnSe window and is focused to a beam diameter of 100 μm by an adjustable ZnSe lens placed inside the chamber. The focus overlaps with the MOT, as shown in Fig. 2. The CO_2-laser beam is left on throughout the MOT formation time. The beam is retroreflected and refocused with a further lens to provide an intense standing wave for the optical lattice. By blocking the retroreflected beam, alternatively a simple dipole trap can be realized. The CO_2-laser beam power is controlled by an acoustooptical modulator, which also provides optical isolation of the laser. The total fluorescence, giving a measure for the number of trapped atoms, is determined with a calibrated photodiode. We also can image the spatial distribution of the atomic cloud with a pulsed intensified camera (ICCD).

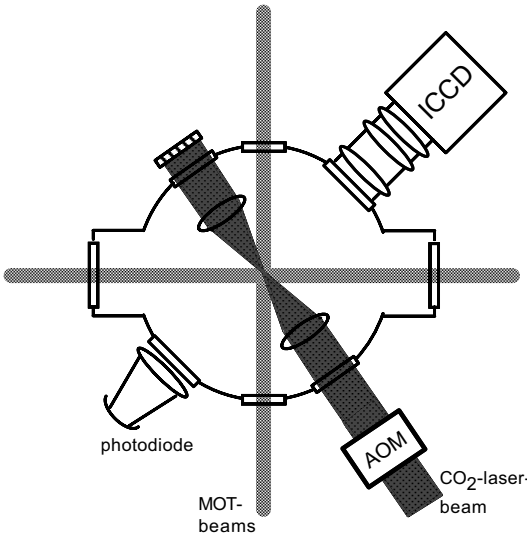

Fig. 2. Schematic of the experimental setup for a cold atom CO_2-laser optical lattice

After the MOT loading period, both the near resonant optical beams and the magnetic field are shut off, while the CO_2-laser beam remains on. The atoms are trapped in the potential induced by the infrared standing wave only. After a variable trapping time, the near-resonant MOT cooling and repumping beams are pulsed on again, and the resulting fluorescence is measured.

4 Results

Typical fluorescence images as detected with an ICCD camera during different times of the loading and detection phase are shown in Fig. 3. After the initial MOT (A) and the far-detuned dark MOT phase (B), the atoms are trapped by the far-detuned CO_2-laser beam. During this time no fluorescence is detected (C). The final picture gives an image of the trapped atoms scattering near-resonant laser light (D). The transverse dimension of the image is determined by the finite resolution of our imaging system. The finite resolution presently also prevents us from spatially resolving the lattice periodicity. We currently trap typically 3×10^5 atoms in the infrared standing wave. This represents about an order of magnitude improvement compared to our earlier published data [2], where atoms were still loaded from a normal MOT. The observed trap lifetime is 1.8 s and is limited by the finite vacuum background pressure.

The temperature of the trapped atoms has been measured with a time-of-flight technique by rapidly shutting off the CO_2-laser beam with the acoustooptical modulator, pulsing on the near-resonant detection beams after a variable delay time and analyzing the measured size of the imaged expanded atomic cloud for different delays. The measured atomic temperatures are plotted in Fig. 4 as a function of the cooling laser detuning during the dark MOT phase Δ_2 from the $F' = 4$ hyperfine excited state for both the optical lattice and a simple CO_2-laser dipole trap. The position of the $F' = 3$ excited state is also indicated. Note that both marks correspond to the position of the resonances for a free atom. As indicated by the vertical lines, the position of the resonance of atoms trapped by the CO_2-laser field is shifted due to the difference in ac-Stark shift of ground and excited states to the red. The optical cooling beams will thus appear further blue-detuned to the atoms, thus shifting red-detuned optical beams closer into resonance. For all measured detunings the temperature of the atoms in the optical lattice is above that of the dipole trap, which we ascribe mainly to the increased photon reabsorption probability in the lattice caused by the

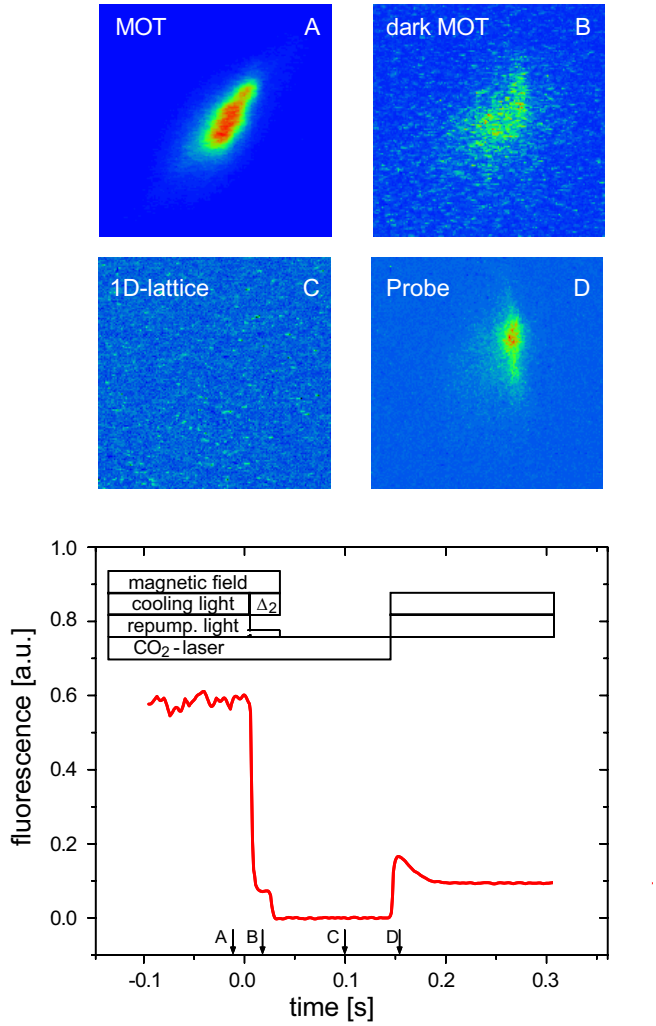

Fig. 3. (*Top*) False-color images of the atomic fluorescence, as detected with an ICCD camera, during the MOT loading (A), dark MOT (B), optical lattice (C) and detection (D) phase. (*Bottom*) The plot gives the total atomic fluorescence, as measured with a photodiode, versus time. The inset shows the experimental timing sequence. For the dark MOT period, both the change in detuning of the cooling laser and intensity of the repumping laser are indicated

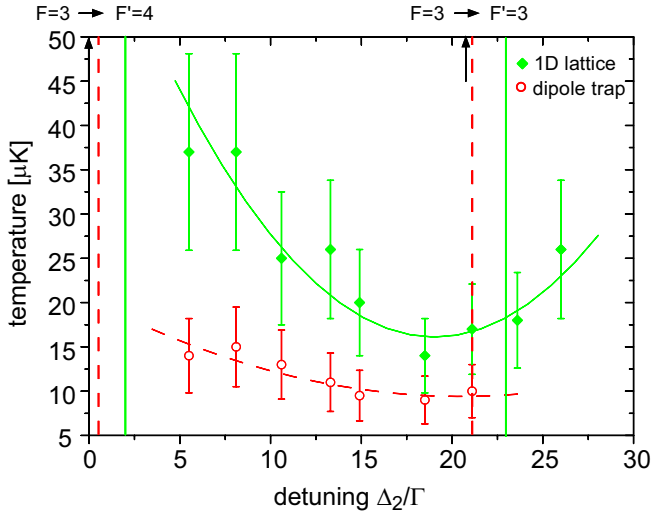

Fig. 4. The plot shows the measured atomic temperature for the dipole trap (*dashed red line*) and the optical lattice (*solid green line*) as a function of the cooling-laser detuning (in units of the natural linewidth $\Gamma = 2\pi \times 6\,\mathrm{MHz}$) during the dark MOT period respectively to the $5S_{1/2}$ ($F = 3$) to $5P_{3/2}$ ($F' = 4$) transition. The position of the transitions from $5S_{1/2}$ ($F = 3$) to the $F' = 3$ and $F' = 4$ substate of the $5P_{3/2}$ upper level are indicated for a free atom by *arrows*, and for an atom trapped in the center of the dipole trap or a microtrap of an optical lattice by *red* respectively *green vertical lines*. As indicated in Fig. 1 for an optical lattice, the optical resonance frequencies of trapped atoms are shifted due to the difference in the ac-Stark shift of ground and excited states

higher atomic density. Note further, that the potential depth of the lattice is considerably above that of the dipole trap. The minimum atomic temperatures are typically 15 μK for the lattice and 9 μK for the dipole trap. Compared to the case of a laser detuning near the $5S_{1/2}$ ($F = 3$) to $5P_{3/2}$ ($F' = 4$) transition, where conventional red Sisyphus cooling [4] occurs, the measured temperatures at larger detunings are smaller. The influence of the other excited state hyperfine sublevel will in this case lead to other Sisyphus cooling mechanisms [23], which can result in lower temperatures. When tuning the laser even to the red side of the $5S_{1/2}$ ($F = 3$) to $5P_{3/2}$ ($F' = 3$) resonance we observe a decreased number of trapped atoms.

The interaction of a single laser coupling a ground state of total angular momentum F simultaneously to two excited states of total angular momentum $F' = F$ and $F' = F + 1$ – as done here in a three-dimensional configuration – has been investigated experimentally by Esslinger et al. [21] in a one-dimensional optical lattice. The laser frequency was tuned in between these two upper hyperfine levels (but closer to the level with $F' = F$) with orthogonal linear optical polarizations. In that one-dimensional case the polarization changes periodically from σ to π polarization along the standing wave axis. For example, in the regions of pure σ^+ polarization the atoms are optically pumped into the $m_F = F$ ground state sublevel that does not couple to the $F' = F$ excited state. The scattering rate is thus strongly reduced, since the detuning from the $F' = F + 1$ transition is relatively large. In the regions of linearly polarized light all ground state sublevels couple to the light also via the more closely resonant $F' = F$ transition, and due to the blue detuning are ac-Stark shifted toward higher energy. When an atom moves into such a region, it loses kinetic energy and experiences an increased optical pumping rate. The atoms experience Sisyphus cooling and are accumulated in the regions of pure σ polarization in levels coupling only weakly to the light field. This one-dimensional scheme can not only provide cooling, but also trapping of atoms, leading to a near-resonant dark optical lattice.

In our three-dimensional experiment similar polarization gradients varying from σ to π polarization are present. Strong evidence for the occurence of the described combined blue and red Sisyphus cooling mechanism is given by the measured atomic temperature dependence of Fig. 4. Note that in our case the fluorescence of the atoms is further reduced by the fact that the lowered intensity of the repumping laser leaves the atoms most of their time in the lower hyperfine state. In the future, we plan to compare the present cooling technique with an almost pure blue Sisyphus cooling scheme [12] by using the rubidium D1 line with its larger upper state hyperfine splitting.

With the goal of a more complete characterization of our atom traps and, most importantly, to show that the atoms are

actually localized in the antinodes of the CO_2-laser standing wave, we have measured the vibrational frequencies of the trapped atoms by periodically modulating the potential depth. We have performed this measurement for both the CO_2-laser optical lattice and an ordinary dipole trap. When the modulation frequency equals twice the vibrational frequency of the atoms, parametric resonances are excited. More generally, including subharmonics, parametric resonances occur at $\omega_{\mathrm{mod}} = 2\omega_{\mathrm{atom}}/n$ with n as an integer [24]. When such a resonance occurs, the atoms gain potential energy exponentially with time and are heated rapidly out of the trap. With a subsequent detection laser pulse, we then observe less fluorescence.

Figure 5 shows typical vibrational spectra still measured with our old atom loading scheme [2]) as a function of the modulation frequency, and the corresponding vibrational modes. The upper spectrum was obtained with an ordinary dipole trap, and shows principal resonances at $2\omega_z \simeq 2\pi \times 80$ Hz and $2\omega_r \simeq 2\pi \times 1.6$ kHz corresponding to vibrational modes along and orthogonal to the infrared beam axis in this trap. The lower spectrum was recorded with an optical lattice, where principal resonances at $2\omega_r \simeq 2\pi \times 2$ kHz and $2\omega_z \simeq 2\pi \times 32$ kHz are observed. The higher frequency resonance at vibrational frequency $\omega_z \simeq 2\pi \times 16$ kHz – corresponding to an oscillation along the beam axis – reflects the strong confinement in the 5.3 μm periodicity standing wave. Both spectra also show some subharmonic resonances. The measured positions of the resonance frequencies in the lattice spectrum are determined by the average values of the resonance frequencies of the individual microtraps. For the optical lattice, the vibrational frequency along the beam axis exceeds the photon recoil energy in frequency units $\omega_{\mathrm{rec}}/2\pi = \hbar/2m\lambda^2$ (approximately 3.8 kHz) for rubidium, where we have used the wavelength $\lambda \approx 780$ nm of the D2-line cooling transition. The Lamb–Dicke limit is thus fulfilled along this axis.

By use of the measured vibrational frequencies and the atomic temperatures we can determine the actual size of the trapped atomic cloud. Assuming a harmonic trap, the average potential energy per dimension is $kT/2 = (1/2)m\omega_i^2\langle x_i^2\rangle$, where ω_i denotes the vibrational frequency along one axis and $\langle x_i^2\rangle$ the mean quadratic spatial extension of the atomic cloud. Taking the values $\omega_r \approx 2\pi \times 720$ Hz and $\omega_z \approx 2\pi \times 15$ kHz for the lattice (these values were measured in the data aquisition period where the described atomic temperature measurements were recorded), we obtain an average rms size of the microtraps of $r_{\mathrm{rms}} \approx 8.4$ μm and $z_{\mathrm{rms}} \approx 0.41$ μm. For a Gaussian spatial distribution of the atomic ensemble and 14 000 trapped atoms per lattice site we derive a central atomic density of $n \approx 3.1 \times 10^{13}$ atoms/cm^3. With these values we derive a phase-space density $n\lambda_{\mathrm{dB}}^3 \approx 1/300$, which however still must be divided by the number of populated m_F levels of the $F = 2$ ground state. Although one expects that the polarization gradient cooling mechanism locally optically pumps the atoms into only few magnetic substates, in future experiments the atomic sample should be optically pumped into a single magnetic substate after the cooling sequence. For the dipole trap, we derive an atomic density of $n \approx 2.6 \times 10^{12}$ atoms/cm^3 and $n\lambda_{\mathrm{dB}}^3 \approx 1/1500$. We have found the atomic temperature to be slightly dependent on the atomic densities, with a typical slope of 2 μK/10^{12} cm^{-3} measured so far only in the simple dipole trap. We ascribe this density dependent heating to the reabsorption of fluorescence photons. We expect that this slope can be decreased by using more efficient cooling mechanisms, and by using smaller traps. Moreover, in a recent theoretical work Cirac et al. showed, that the problem of reabsorption can be avoided also in optically thick atomic samples by use of a sufficiently slow repumping process [25]. A detailed study of these heating processes remains an important issue of future research.

5 Conclusions

We have described the trapping of laser-cooled atoms in the antinodes of a standing wave near 10.6 μm. Intriguing properties of the resulting one-dimensional optical lattice are long

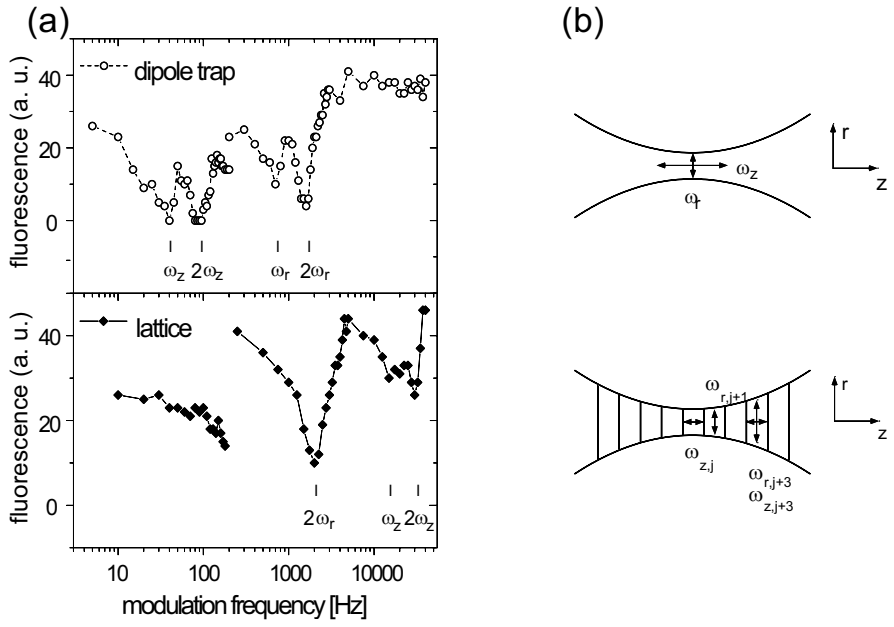

Fig. 5. a Experimental vibrational spectra of rubidium atoms confined in CO_2-laser optical traps. The *upper curve* gives the fluorescence of atoms in an ordinary dipole trap after periodic modulation of the potential depth as a function of the modulation frequency, the *lower spectrum* gives such a spectrum for an one-dimensional optical lattice. For modulation frequencies below 200 Hz it was necessary to use an increased modulation amplitude. **b** Corresponding vibrational modes in the dipole trap (*top*) and the optical lattice (*bottom*)

coherence times and a large lattice spatial periodicity. The obtained atomic phase-space densities are currently of the same order of magnitude as those obtained in two other optical cooling experiments in dipole traps, which however take advantage of more refined cooling techniques. For the present parameters of the optical lattice, one would have to cool the atoms to a temperature of approximately 2 μK to reach quantum degeneracy after spin-polarizing the atoms. The transition temperature would increase with a stronger focusing of the optical beams, and more drastically when moving to a three-dimensional optical lattice, as possible by crossing four or six focused CO_2-laser beams. In a three-dimensional optical lattice one would expect transition temperatures of up to several tens of μK. In addition to increasing the trap steepness, one can also try to optimize the laser-cooling technique. Lower atomic temperatures could be possible by the use of gray molasses [12] or Raman cooling [10, 11]. Whereas in our present one-dimensional setup the Lamb–Dicke regime is fulfilled in one dimension, in a three-dimensional lattice this condition can easily be fulfilled for all spatial dimensions, such that efficient three-dimensional sideband cooling of the trapped atoms should then be possible. Inspired by work on ion trapping [14–16], one could start by cooling a single atom into the ground state of a trap. The adding of more and more atoms would allow a very direct study of atom–photon interactions, and could allow the observation of quantum degeneracy using laser cooling only, or the realization of an array of 'atom lasers'.

Many other directions of research with the CO_2-laser optical lattice can be envisioned. Contrary to near-resonant optical lattices, the large individual lattice sites can be spatially resolved with an optical microscope. The long coherence times possible with the far-detuned optical trap are of crucial importance for experiments studying quantum coherence or entanglement with trapped atoms. Further applications in the field of quantum logic with neutral atoms should be possible [2].

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