Resolving and addressing atoms in individual sites of a CO_2-laser optical lattice

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We report on the microscopic imaging of individual sites of an optical lattice with a period of 5.3 μm created by a retroreflected, focused CO_2-laser beam. In this one-dimensional lattice, the Lamb-Dicke limit is fulfilled in all three spatial dimensions. Single lattice sites have been individually addressed with a focused near-resonant laser beam. Because of the negligible decoherence rate from spontaneous photon scattering such a lattice holds intriguing prospects for the realization of fault-tolerant quantum logic gates.

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Cold atoms can be trapped by dipole forces in the periodic potential created by interfering laser beams, thus creating an optical lattice [1]. Such systems have attracted considerable interest due to the possibility of a simple and flexible manipulation of their solid-state-like periodic potential. Optical lattices have been used as model systems in studies of quantum-dynamical effects like quantum chaos [2] and quantum transport [3]. Moreover, in optical lattices the Lamb-Dicke regime is readily reached, where the spacing of vibrational levels exceeds the photon recoil energy. This suggests that the trapped atoms could be cooled to the vibrational ground state by sideband cooling, as demonstrated in pioneering experiments with single ions in Paul traps [4]. With neutral atoms, sideband cooling to the ground state of a three-dimensional optical lattice has recently been achieved [5]. Atoms in the ground state of an optical lattice could provide an intriguing system to explore quantum state control [6]. Recently, it has been pointed out that optical lattices would provide an attractive physical system for performing quantum logic experiments [7–10]. In far-detuned lattices neutral atoms couple only very weakly to the environment, so that the decoherence rate can be kept small. Most importantly, very efficient schemes for quantum error corrections [11] and fault-tolerant computing [12] can be straightforwardly implemented due to the inherent possibility of parallel operation [13]. On the other hand, the possibility of selectively addressing and manipulating single qubits is central to the operation of quantum logic systems. This is difficult to achieve in conventional optical lattices, where the spatial period is of the order of half the wavelength of an atomic absorption line. Traditionally, optical lattices have therefore been investigated by monitoring their (quantized) vibrational frequencies [1]. A periodic trapping potential for atoms with large trapping site spacing can, for example, be created by optical imaging of mechanical microstructures, as, e.g., a grating, which allows for the resolving of individual lattice sites [14].

In this Rapid Communication, we report on the optical imaging of rubidium atoms trapped in an extremely far-detuned optical lattice formed by an infrared standing wave

near $\lambda_{trap}=10.6$ μm. The use of this midinfrared trapping radiation with a wavelength of more than an order of magnitude above that of the lowest absorption line of the rubidium atom allows the generation of a ''mesoscopic lattice'' in a standing light wave, where the lattice spacing $\lambda_{trap}/2$ is directly related to the well-controlled frequency of light. Moreover, extremely long atomic coherence times are expected in this lattice, as required for experiments studying quantum entanglement and quantum logic. The fluorescence emitted by rubidium atoms trapped in individual sites has been imaged by an optical microscope, yielding direct evidence for the lattice structure. To our knowledge, this represents the first observation of individual lattice sites with periodicity near half the trapping wavelength. Furthermore, we have been able to manipulate atoms confined in the single lattice sites by illuminating them with a pulse of resonant light. Preparation and readout of individual qubits should hence be possible in this kind of optical lattice.

As in other optical dipole force traps [15], the trapping potential in optical lattices is based on the interaction of an induced atomic dipole moment with an off-resonant laser field. When the laser frequency is tuned to the red side of an atomic transition, the atoms are attracted towards the maximum field intensity and the trapping potential is given by $U=-\frac{1}{2}\alpha|\mathbf{E}|^2$. Here α is the atomic polarizability and $|\mathbf{E}|$ is the amplitude of the light field. Since the frequency of the trapping laser in our experiment is much smaller than that of the lowest atomic dipole transition in rubidium, the polarization α can be approximated by its static value, and spontaneous scattering is largely suppressed [16]. For our experimental parameters, the expected time to spontaneously scatter a photon is above 600 s. As in our earlier work [7], we use a retroreflected focused CO_2-laser beam near 10.6 μm to realize a midinfrared lattice. The atoms are polarization gradient cooled into pancake shaped microtraps spaced by 5.3 μm. This one-dimensional (1D) arrangement minimizes the heating rate due to reabsorption of fluorescence photons from neighboring lattice sites. With proper focusing of the trapping light, the transverse atomic confinement can be made sufficiently large that the Lamb-Dicke limit $\sqrt{\omega_{rec}/\omega_{osc}}<1$ is not only fulfilled along the lattice axis, but also in all other spatial dimensions. This is an important prerequisite for future three-dimensional sideband cooling of the trapped atoms [4].

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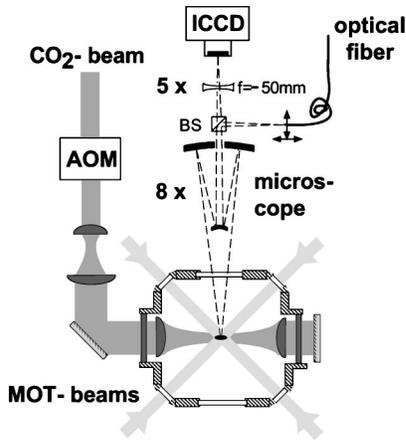
FIG. 1. Schematic of the experimental apparatus.

Our experimental setup shown in Fig. 1 is similar to that described previously [7,17]. The vacuum system has been improved to achieve better optical access to the trap region and longer lifetimes. The 1D optical lattice is created by a single-mode CO_2 laser generating an output power of up to 50 W near 10.6 μm. Its infrared beam passes through an acousto-optic modulator (AOM), which is used both for optical isolation and to control the beam intensity. Two adjustable ZnSe lenses inside the vacuum chamber and a retrore-flecting mirror are used to form a standing wave with a beam waist of typically 35 μm. With an input power of 14 W at this beam waist the calculated trap depth [7] is $U_0/h = 43.5$ MHz, which corresponds to a temperature of 2.1 mK. The optical lattice is loaded by means of a magneto-optical trap (MOT) that collects and precools ^{85}Rb atoms.

The trapped atoms have been imaged with a Questar long-distance microscope QM100 placed 10 cm away from the trap center outside the vacuum system onto an intensified charge-coupled-device (ICCD) camera. To image individual lattice sites, we have inserted an additional biconcave lens of $f = -50$ mm focal length between microscope and camera, which results in an enlargement of the original image by an additional factor of 5. With this total magnification of 40 the rescaled pixel size is 0.6 μm. For some of the measurements, light from an additional laser tuned to the $5S_{1/2}$, $F = 3$ to $5P_{3/2}$, $F' = 4$ cycling transition has been sent through the core of an optical fiber and is imaged via a beam splitter through the microscope onto the sample. The optical setup here represents that of a confocal microscope, and allows the illumination of only a small area of the trap region.

In a typical experimental run, we collect about 5×10^7 ^{85}Rb atoms during a MOT loading period of 3 s. The atoms are then compressed for 20 ms in a temporal dark MOT realized by detuning the cooling laser 13 linewidths to the red side of the cooling transition and by simultaneously reducing the repumping laser intensity by a factor of 10. During this phase the CO_2-laser beam, with its focus superimposed on the MOT region, is activated. At the end of the dark MOT phase, all resonant beams are extinguished and the magnetic field is switched off. The number of atoms that remain trapped in the optical lattice, as well as their spatial extension, are measured by pulsing on the MOT beams and

imaging the fluorescence onto both a calibrated photodiode and the ICCD camera. Typically, we load around 1×10^6 ^{85}Rb atoms into the lattice, distributed over roughly 100 lattice sites. We have observed a lifetime of 3.4 s, limited by collisions with the thermal rubidium background gas.

The vibrational frequencies have been measured by parametrically exciting the atoms as described previously [7]. Briefly, the CO_2-laser beam intensity is periodically modulated by the AOM, leading to significant vibrational excitation and subsequent trap loss if the modulation frequency equals twice a trap vibrational frequency. With the typical parameters of 14 W and 35 μm, we measure oscillation frequencies in the central trap region of $\nu_z = 54(5)$ kHz in the axial and $\nu_r = 4.2(5)$ kHz in the radial direction. The Lamb-Dicke limit, corresponding to an oscillation frequency above $\nu_{rec} = 3.8$ kHz, is therefore fulfilled in all three spatial dimensions. We have determined the temperature of the atoms by switching off the trapping potential and observing the ballistic expansion of the cloud, with the CCD camera using a magnification of only a factor of 8. We measure a temperature of 70 μK for ^{85}Rb at the quoted trap depth, almost a factor 5 above the results of our previous works [7,17] taken with lower trapping beam intensities. When decreasing the CO_2-laser intensity, the measured temperature reduces to 10 μK and the atomic phase-space density $n\lambda_{dB}^3$ reaches its maximum value, being as high as 1/300. On the other hand, when increasing the trapping beam laser power the atomic temperature rises to values approaching the Doppler temperature limit of 140 μK. We attribute this effect to the fact that upper and lower electronic states are ac Stark shifted by different amounts in the presence of the CO_2 laser field. The static polarizability of the upper state is about a factor of 2.5 above that of the ground state. For larger laser power, the differential ac Stark shift becomes comparable to the ^{85}Rb upper state hyperfine splitting and the efficiency of sub-Doppler laser cooling is strongly reduced. Therefore the best starting point for Raman-sideband cooling would be to first load the lattice at low power to achieve high phase-space densities, and subsequently ramp up the potentials adiabatically to maximize the vibrational trap frequencies.

After optimization of the trap parameters as described, we proceeded to image the optical lattice. For these experiments, the power of the CO_2-laser beam was reduced to 4 W to achieve lower temperatures. After loading the lattice and holding the atoms for 100 ms, the CO_2-laser beam was shut off to avoid a position-dependent ac Stark shift, and the MOT lasers were pulsed on for 20 μs while accumulating the atomic fluorescence with the ICCD camera. We have chosen the detuning of the cooling laser to be resonant with the cycling transition and also added repumping light. Figure 2(A) shows the image of 50 accumulated recordings after subtracting a constant background due to spurious scattered light and dark counts. The atoms are localized in periodically spaced pancakelike microtraps of 5.3-μm period, each of these sites now containing roughly 4×10^3 atoms. From Fig. 2(B) showing a cross section of the lattice image we can evaluate a contrast defined as $C = (I_{max} - I_{min})/(I_{max} + I_{min})$ of 32(5)%, which gives a quantitative measure for the resolving of the lattice. From the measured vibrational
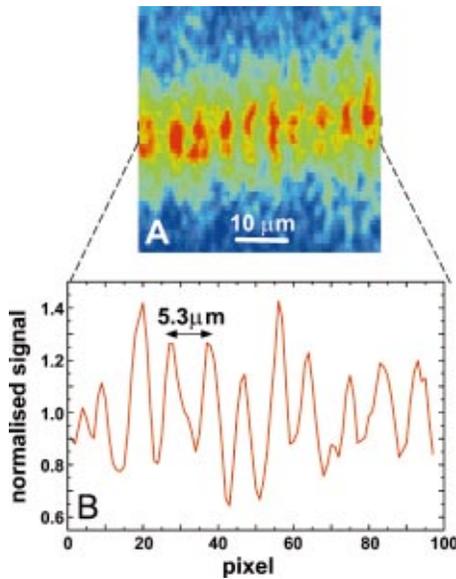
FIG. 2. (Color) (A) Image of rubidium atoms trapped in a one-dimensional optical lattice with a period of 5.3 μm. The axis of the infrared CO_2-laser beam is oriented horizontally. (B) Cross section of this image obtained by integrating the measured atomic fluorescence perpendicular to the trapping beam axis.
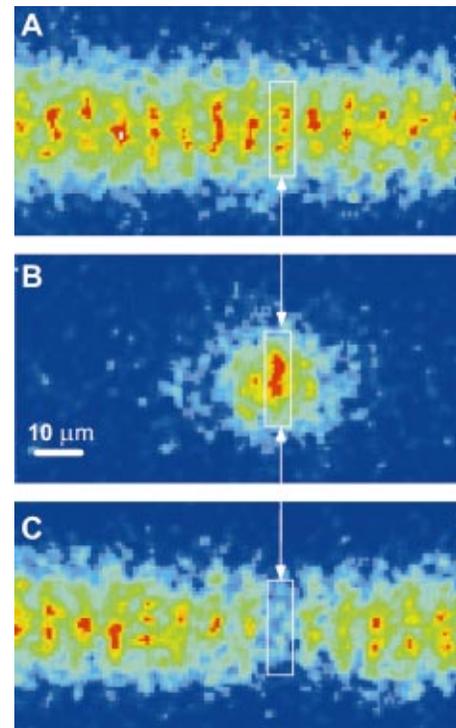

FIG. 3. (Color) Images of the lattice after the following manipulations: (A) no manipulation of the atoms in the microtraps; (B) only atoms from a single lattice site illuminated during the exposure with a focused laser beam; (C) after removing atoms in one lattice site before the exposure.

frequencies and the atomic temperature ($T=52$ μK for this data set), we can estimate the actual size of the atomic microclouds when assuming $k_B T/2 = 2\pi^2 m \nu_i^2 \sigma_i^2$ for atoms in a harmonic potential. The calculated radial width $\sigma_r^{theo}=5.2$ μm of the atomic distribution is in reasonable agreement with the measured value of $\sigma_r=6.8(7)$ μm half-width at half maximum, which was obtained assuming a Gaussian atomic density distribution in the trap. The calculated axial width of the microclouds is $\sigma_z^{theo}=0.4$ μm, which is far less than the lattice spacing (5.3 μm) and would result in an expected contrast of 100% for the lattice cross section. We attribute the measured contrast to being mainly limited by the finite resolution of our imaging system. We have modeled the image by convoluting the expected picture with a Gaussian broadening of variable width. From a fit of this simple model to the cross section of Fig. 2(B), we derive an estimated spatial resolution of 1.9 μm for our imaging system. The measurements show that it is possible to distinguish atoms in neighboring lattice sites and thus read out the information of individual quantum bits stored in the antinodes of this 1D optical lattice.

Figure 3(A) shows the image of the lattice illuminated by the MOT beams, similar to that already described. The CO_2 trapping laser was left on during the entire cycle. This allowed illumination times as long as 100 μs. In the absence of the trapping field, the contrast of the images vanishes within 30 μs, due to the thermal expansion of the cloud. The MOT cooling beams were resonant with the $5S_{1/2}$, $F=3$ to $5P_{3/2}$, $F=4$ cycling transition at the bottom of the central potential wells to account for the ac Stark shift. Figure 3(B) depicts an image taken by illuminating a single trapping site for a period of 100 μs with around 10 μW of light resonant with the cycling transition at the bottom of the trap through the fiber

and by the MOT repumping beams. The exposure shows atoms localized in one distinct potential, with the neighboring lattice sites suppressed by a factor of approximately 2.3. Note that the rest of the lattice is still filled, but is not visible here. This shows that, in principle, it is possible to address single qubits in an optical lattice. In order to investigate whether the neighboring wells were being perturbed by the focused laser beam, the following procedure was used. After loading the atoms into the trap, we applied a 10-μs-long pulse of light through the fiber with the same frequency, but with 20 times higher intensity. Again the MOT repumping beams were used to provide the necessary repumping light. Figure 3(C) depicts the image of the lattice after interaction with such a pulse using the MOT beams for exposure of the picture. The population of a single lattice site has been almost completely removed, while atoms in the neighboring sites are affected much less by the optical pulse. By varying the position of the optical fiber along the axial direction of the lattice we could address different lattice sites within our optical field of view, which comprises around 50 lattice sites. While at present we used an imaging system optimized for the visible spectral region, the optical resolution could be further improved with a system optimized for the atomic fluorescence wavelength of 780 nm for the rubidium $D2$ line. Alternatively, one could use shorter wavelength transitions for the fluorescence imaging, e.g., the $5S$-$6P$ line of the rubidium atom near 420 nm.

In the future, we wish to explore the possibility of performing quantum logic operations with this far-detuned op-

tical lattice. To avoid rapid decoherence, the atoms must be cooled to the vibrational ground state of the lattice, which should be possible with sideband cooling techniques [4,5]. Note that, while in dense atomic samples the efficiency of laser cooling is usually limited by reabsorption of fluorescence photons, for quantum logic experiments the cooling of a single atom per lattice site into the ground state is sufficient (and required for the proposals considered up to now). The detection of single, trapped atoms requires efficient fluorescence detection and has been achieved in several laboratories [18].

A coupling of atoms in different lattice sites should be possible, e.g., by dipole-dipole interactions [8], controlled cold collisions [9], or high finesse optical cavities [10,7]. The former two are local interactions, and a coupling can be achieved with a state-dependent lattice geometry that requires additional closer-resonant optical manipulation beams with detuning comparable to the atomic fine structure, i.e., tuned between the $P_{1/2}$ and $P_{3/2}$ levels. It has been pointed out that fault-tolerant quantum logic operation can be realized in optical lattices, as a shift operation on a lattice plane can lead to the simultaneous entanglement of many atoms by, e.g., cold collisions, thus allowing for a considerable redundancy in the operations [13]. The CO_2-laser lattice allows a very controlled loading of the near-resonant manipulation lattice, while the possibility of spatially resolving the individual qubits can be maintained. Let us assume that a stand-

ing wave of the near-resonant beams is oriented along the same axis as the midinfrared wave generated by the CO_2 laser, and the CO_2-laser wavelength is chosen such that it equals an integer multiple of the near-resonant light, e.g., $\lambda_{CO_2} = 13\lambda_{opt}$ for the rubidium atom. After preparing the qubits in the CO_2-laser lattice, the retroreflected 10.6-μm beam is extinguished and the closer-resonant light activated, while the atoms still hold against gravity with the traveling-wave CO_2-laser beam. The atoms are then transferred into the near-resonant standing wave, with precisely every 13th trapping site occupied by an atom. The described scheme should enable the realization of entangled two- and more particle quantum states with the possibility of addressing individual atoms. The realization of highly parallel quantum gates in an optical lattice would represent an important step towards a fault-tolerant quantum computer.

To conclude, we have optically resolved an optical lattice based on the radiation of a CO_2 laser operating near 10.6 μm. This type of optical lattice has exciting prospects for quantum logic experiments. In addition our 1D geometry minimizes reabsorption of spontaneously emitted photons. This could allow for the possibility of reaching Bose-Einstein condensation by optical cooling alone.

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