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CO_2-laser optical lattice with cold rubidium atoms

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Laser-cooled rubidium atoms have been trapped in a nondissipative optical lattice with a large lattice constant. The lattice potential is generated by the ac Stark shift in an infrared standing wave near 10.6 μm. The atoms are confined in steep potential wells with a periodicity of several micrometers. By modulating the potential depth we parametrically excite the atoms and measure their vibrational frequencies. [S1050-2947(98)50901-8]

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In optical lattices [1] electric-dipole forces associated with the ac Stark effect confine cold atoms to arrays of microscopic potential wells formed by interfering laser beams. In a reversal of familiar roles, matter waves are thus oscillating in cavities made of light. The lattice potential can be controlled by modulating the intensity, phase, or polarization of the laser beams, as exploited in recent studies of quantum chaos [2], Bloch oscillations [3], Wannier-Stark ladders [4], atom tunneling [5], or the parametric excitation of atomic wave-packet oscillations [6]. Lattices with near-resonant trapping fields readily reach the Lamb-Dicke regime where the spacing of vibrational levels exceeds the photon recoil energy. Here, laser cooling alone can accumulate a large fraction of the atoms in the lowest vibrational state, since the accessible phase space is much restricted by the trapping potentials. If an average population of more than one atom per lattice site could be realized, the quantum degenerate regime could be reached by purely optical methods, without the need for evaporative cooling, which has been a key for the Bose-Einstein condensation of ultracold alkali-metal atoms [7]. Unfortunately, the atom density in optical lattices has so far been limited to about 10^{11} atoms/cm^3 by radiative repulsion and light-assisted collisions so that at most a few percent of the lattice sites are occupied. Moreover, the damping of the atomic motion by spontaneous scattering forces leads to considerable quantum decoherence. One approach to circumvent these problems employs dark optical lattices [8] where the scattering rate is reduced by optically pumping the atoms into dark states. Alternatively, optical lattices with a far-detuned trapping field have been demonstrated [9] that are reaching spontaneous photon scattering times in the millisecond range at detunings of a few nanometers.

In this Rapid Communication we report on the trapping of rubidium atoms in an extremely far detuned optical lattice using an infrared standing wave near 10.6 μm. The expected average time for an atom to spontaneously scatter a photon is 20 min. Hence the atoms are confined in a highly conservative potential. Furthermore, the lattice constant is more than an order of magnitude larger than that of near-resonant optical lattices. Due to the large volume, each unit cell contains a much larger atomic population. In addition, the laser-induced fluorescence of the atoms in each individual lattice site could be spatially resolved with a suitable microscope.

A one-dimensional (1D) infrared optical lattice can be realized by retroreflecting a focused CO_2-laser beam. For a waist size of the focus of 50 μm and 5-W power from the CO_2 laser, the ac Stark shift of the atomic energy levels due to the lattice laser is $2\pi\times 8$ MHz at the site of an antinode. This corresponds to a potential depth of 360 μK and is at least ten times larger than the kinetic energy of the laser-cooled atoms. Hence, the dipole force provides a strong spatial confinement of the atoms. We have measured the atomic vibrational frequencies of both an infrared optical lattice and a simple dipole trap (realized by a focused traveling beam) by modulating the potential depth and thus parametrically exciting atomic vibrations. We observe for the lattice geometry a drastically increased oscillation frequency along the beam axis caused by the stronger axial confinement of the atoms in the intensity maxima.

In optical dipole traps atoms are attracted towards the maximum of the field intensity, if the laser frequency is tuned to the lower frequency (red) side of an atomic transition. The trapping potential for atoms is given by the ac Stark shift $V=-(1/2)\alpha|E|^2$, where E is the electric-field amplitude and α denotes the atomic polarizability. For a CO_2-laser dipole trap [10] the atomic polarizability can be approximated by its static value α_s. Since this quantity is positive for both the ground and the excited state, the potential is confining for atoms in both levels, unlike in the case of conventional dipole traps [11], where the ground state is trapped in a region of high intensity, while the excited state is repelled.

Now consider a 1D dipole force lattice realized by a CO_2-laser standing wave along the z axis. The Stark-shift potential is given by

$$V(r,z)=4V_{max}\exp[-2r^2/w(z)^2]\cos^2(2\pi z/\lambda),$$

with $V_{max}=\alpha_s P/[c\epsilon_0\pi w(z)^2]$, where P denotes the optical power and $w(z)$ the beam radius. The potential, as depicted in Fig. 1, has a periodicity of 5.3 μm. The excited state is more tightly bound than the ground state. The atoms are trapped at the antinodes of the standing wave. At each antinode the potential can be approximated by a harmonic-oscillator potential $V_j(r,z)=(m/2)\omega_{jr}^2 r^2+(m/2)\omega_{jz}^2 z^2$. The different vibrational modes are depicted in Fig. 2. The vibra-

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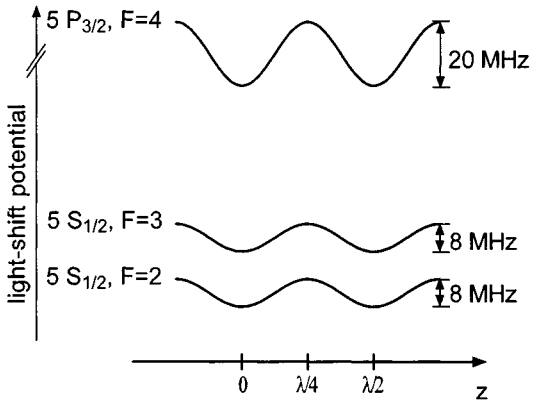

FIG. 1. Light-shift potential of the two hyperfine ground-state levels $5S_{1/2}$ ($F=2,3$) and the $5P_{3/2}$ ($F=4$) excited state in a standing wave near 10.6 μm. The values for the potential depth are given for a $w_0=50$ μm focus of a 5-W CO_2-laser beam using the scalar polarizability. Note that the atomic transition frequencies of the atoms trapped at the antinodes of the light field are shifted to lower frequencies, since the excited state is trapped more strongly than the ground state.

tional frequencies are given by $\omega_{jr}=\omega_r^{max}\sqrt{1-4(z_j/z_R)^2}$ with $\omega_r^{max}=\sqrt{16\alpha_s P/(c\epsilon_0 m\pi)}/w_0^2$ in the transverse direction and $\omega_{jz}=\omega_z^{max}\sqrt{1-2(z_j/z_R)^2}$ with $\omega_z^{max}=\sqrt{32\pi\alpha_s P/(c\epsilon_0 m)}/(w_0\lambda)$ in the longitudinal direction. For rubidium atoms in a 5-W CO_2-laser standing wave focused to a waist radius of 50 μm, the expected vibrational frequencies in the center of the lattice are 1.2 kHz transversely and 25 kHz longitudinally.

In our experiment we capture laser-cooled rubidium atoms from a magneto-optic trap (MOT) [12]. A scheme of the setup is shown in Fig. 3. The cooling and repumping beams at 780 nm are provided by grating stabilized diode lasers. For the dipole trap and optical lattice, we use a single-mode CO_2 laser with a power of 10 W. The CO_2-laser beam enters the vacuum chamber through a ZnSe window and is focused by an adjustable ZnSe lens ($f=38$ mm) inside the chamber. The focus ($w_0=50$ μm) overlaps with the trapped atoms in the MOT. The focus of the back reflected beam is adjusted with

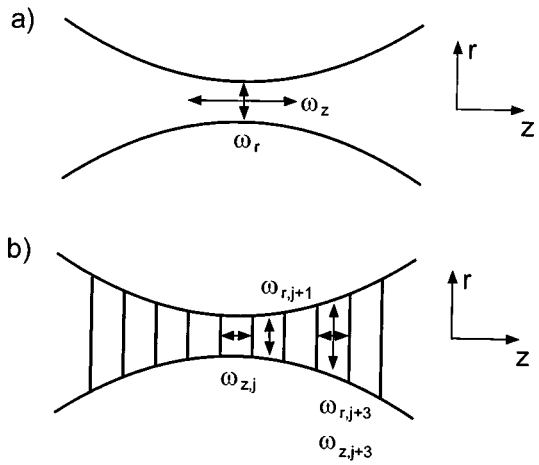

FIG. 2. Sketch of the different vibrational modes of (a) the dipole trap and (b) the lattice. (Not to scale.)

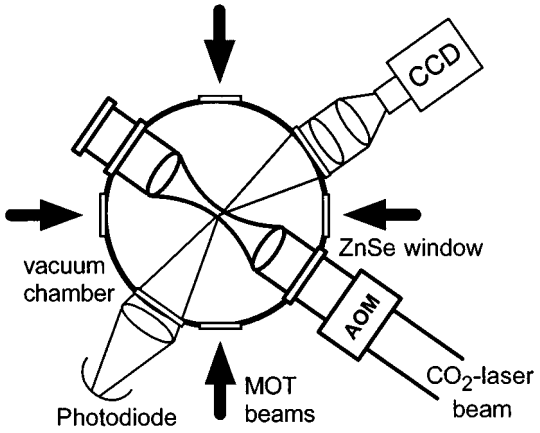

FIG. 3. Schematic of the experimental apparatus.

a second ZnSe lens. The power in the infrared beam can be controlled by an acousto-optic modulator (AOM). The AOM also provides optical isolation of the CO_2 laser from the retroreflected beam. By blocking the retroreflected beam, an ordinary dipole trap can be realized. Fluorescence from the atoms excited with the diode laser field is observed with a photodiode. A charge-coupled-device camera is used to monitor the spatial distribution of the atoms. This is convenient for the alignment of the overlap of the infrared beams with the MOT.

The experiment proceeds in three steps: the lattice is loaded from the MOT, the atoms are then manipulated by modulating the lattice field, and finally the number of atoms that remain in the lattice is probed. We first load atoms from the rubidium vapor pressure (typically 8×10^{-9} mbar) into a MOT for a period of 3 s. In this way a cold sample of atoms (0.3 mm diameter, 10^6 atoms) is prepared. To load the atoms from the MOT into the lattice, the CO_2-laser standing wave remains on during the MOT loading time. As the excited state exhibits a stronger Stark shift than the ground state, the atoms located near the intensity maxima of the 10.6-μm standing wave are almost resonant with the MOT beams. To provide red-detuned cooling beams even for atoms located within the CO_2-laser waist, we shift the frequency of the MOT beams for a period of 30 ms to a value of seven linewidths below the unperturbed atomic resonance. Then the MOT beams and the magnetic field are turned off, leaving only the CO_2-laser standing wave present. By this time the atoms are confined in the optical lattice provided by the CO_2-laser standing wave.

During the second phase of the experiment we manipulate the trapped atoms in the lattice. The intensity of the infrared beam and thus the potential depth are modulated by 30% with a sinusoidal burst signal so that the atoms are forced to oscillate in the wells. If the modulation frequency equals twice the vibrational frequency of the lattice ($\omega_{mod}=2\omega_{lattice}$) atoms are parametrically excited. Also at subharmonic frequencies ($\omega_{mod}=2\omega_{lattice}/n$, where n is integer) parametric resonances can be excited [13]. On resonance the kinetic energy of the atoms increases exponentially with time, and atoms are heated out of the lattice. After a delay time both the cooling and repumping beams are turned on again to probe the fluorescence of the trapped atoms. The fluorescence of the atoms remaining in the lattice after the

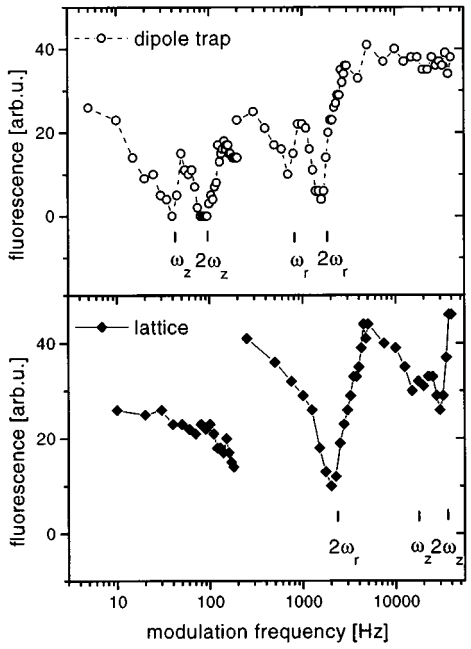

FIG. 4. Experimental spectrum of the vibrational frequencies of atoms in a 10.6-μm optical lattice, and a simple dipole trap. The solid curve shows the fluorescence of the atoms in the lattice after the modulation of the potential depth as a function of the modulation frequency. The hollow circles depict the same measurement taken for a simple dipole trap.

modulation is measured as a function of the modulation frequency for a fixed trapping time of $T=600$ ms. The number of atoms is determined from the fluorescence intensity, taking into account the probe intensity, detuning, geometry, and detection efficiency. We also have blocked the retroreflected beam to realize a dipole trap, and measured the vibrational frequencies by parametrically exciting the atoms in this trap.

Typically 10^4 atoms are trapped in the lattice at the same average density as that of the MOT. The lifetime of the atoms in the lattice is 1.7 s, which is only limited by collisions with background gas atoms. We have measured the energy distribution of the trapped atoms by lowering the potential depth nonadiabatically to a variable value and detecting the number of atoms that remain trapped. From this measurement we estimate a temperature of 18 μK for the atoms in the dipole trap.

Vibrational excitation spectra of trapped atoms are presented in Fig. 4. The fluorescence of the atoms after the modulation of the potential depth is shown as a function of the modulation frequency. The vibrational spectrum of a 1D infrared optical lattice is shown by the solid curve. One recognizes parametric resonances at 2 kHz and at 32 kHz. They correspond to twice the radial vibrational frequency ω_r and twice the longitudinal vibrational frequency ω_z, respectively. Note that one also observes a resonance corresponding to the subharmonic at 16 kHz. The expected subharmonic at 1 kHz is not observed. The dashed curve is obtained for a CO_2-laser dipole trap realized by blocking the back reflected beam. In this spectrum four resonances are observed. The resonance at 1.6 kHz corresponds to twice the radial frequency ω_r, the resonance at 80 Hz to twice the longitudinal frequency ω_z. In this spectrum both subharmonics are resolved. For the dipole trap we do not observe any vibrational structure above 2 kHz. For both spectra the potential depth has been modulated by 30% with one burst of 1000 cycles. To resolve the resonances below 100 Hz, the modulation depth was set to 100% and the number of cycles reduced to 50.

The vibrational spectra reveal that the atoms in the dipole trap oscillate around the center of the trap at $z=0$ and $r=0$ with a single frequency per mode. Approximating the potential of the dipole trap by a harmonic-oscillator potential, one obtains vibrational frequencies of 600 Hz transversally and 40 Hz longitudinally. These calculated frequencies are in fair agreement with the measured frequencies in the spectrum.

The vibrational resonances for the optical lattice appear broadened since we are observing approximately 140 miniature dipole traps. The atoms in the jth trap oscillate around the position $z_j=j\lambda/2$, where now the lattice sites have different vibrational frequencies due to the z-dependent radius of the beam (see Fig. 2). As the width of these multiple resonances is larger than their spacing, they cannot be resolved. The observed resonance is now expected at a weighted average oscillation frequency of the individual microtraps. The contribution of the atoms oscillating in the outer wells shifts this mean oscillation frequency to a value lower than the maximum. The resonances are located at $c_z\omega_z^{max}$ and $c_r\omega_r^{max}$, where $c_z, c_r<1$ depend both on the spatial extension and the atomic distribution in the lattice. A much more detailed study of these trap frequencies will be possible, when vibrational frequencies of individual (or small groups of) trap sites can be measured, which should be possible using an improved imaging system that allows spatial resolving of the fluorescence emitted from atoms in individual trap sites. In our present experiments we do not spatially resolve the fluorescence of individual lattice sites. Due to the inhomogeneous broadening of the oscillation frequencies of the lattice, the amplitudes of the resonances in the vibrational spectrum of the lattice are below that of the dipole trap and their widths are slightly larger.

In conclusion, we have demonstrated a 1D infrared optical lattice at 10.6 μm and measured its vibrational frequencies. This type of optical lattice can be extended to two and three dimensions. Its unique properties are the negligible spontaneous scattering rate, a long storage time, and steep potential wells. The spatial period of the lattice is an order of magnitude larger than that of conventional near-resonant optical lattices. This leads to intriguing future perspectives. As discussed above, it should be possible to spatially resolve the fluorescence emitted from the atoms in each individual lattice site, which also allows a very direct study of transport phenomena, tunneling, and diffusion between the lattice sites. Moreover, the realization of a three-dimensional optical lattice with an average population of more than one atom per lattice site seems feasible, even at only moderate average atomic densities. By crossing four traveling focused CO_2-laser beams, one can create a three-dimensional optical lattice that should trap 20 atoms per lattice cell at the average atomic density of an ordinary magneto-optical trap. The lattice potential of the microtraps should be even steeper than in the one-dimensional case demonstrated here, yielding vibrational frequencies above 10 kHz and possibly up to 100

kHz with higher laser powers. Novel cooling mechanisms can be envisioned, since the electronically excited state is more tightly bound than the equally bound ground states. These are unique conditions for the prospect of observing quantum degeneracy of atoms purely using laser cooling.

An alternative perspective of this work might be the realization of quantum logic gates. Long coherence times are expected, because of the low scattering rate. When filling the lattice with one atom per lattice site, a quantum bit (qubit) could be stored in each atom (e.g., in two Zeeman ground-state levels) and individually addressed with focused laser beams. The atoms could communicate via a single quantized mode of a high-finesse optical cavity [14]. Advantages of this scheme versus, e.g., work on linear ion traps include the possibility of realizing a two-dimensional array of qubits in an optical lattice. Further, note that the distance between neighboring atoms is extremely well controlled here, since it precisely equals half the trapping wavelength. By choosing the trapping wavelength to be an integer multiple of that of the cavity photons, all atoms could be placed precisely at the antinodes of the cavity, resulting in an equal coupling for all atoms to the cavity field.

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