Experiments on trapping ytterbium atoms in optical lattices*

Zhou Min(周 敏), Chen Ning(陈 宁), Zhang Xiao-Hang(张晓航), Huang Liang-Yu(黄良玉), Yao Mao-Fei(姚茂飞), Tian Jie(田 洁), Gao Qi(高 琪), Jiang Hai-Ling(蒋海灵), Tang Hai-Yao(唐海瑶), and Xu Xin-Ye(徐信业)†

State Key Laboratory of Precision Spectroscopy and Department of Physics, East China Normal University, Shanghai 200062, *China*

(Received 7 July 2013; revised manuscript received 4 August 2013)

Experiments on trapping ytterbium atoms in various optical lattices are presented. After the two-stage cooling, first in a blue magneto–optical trap and then in a green magneto–optical trap, the ultracold ^{171}Yb atoms are successfully loaded into one-, two-, and three-dimensional optical lattices operating at the Stark-free wavelength, respectively. The temperature, number, and lifetime of cold ^{171}Yb atoms in one-dimensional lattice are measured. After optimization, the one-dimensional lattice with cold ^{171}Yb atoms is used for developing an ytterbium optical clock.

Keywords: laser cooling and trapping, optical lattices, ytterbium atoms, atomic optical clocks

PACS: 37.10.De, 37.10.Jk, 32.70.Cs, 95.55.Sh **DOI:** 10.1088/1674-1056/22/10/103701

1. Introduction

With the help of optical lattices, studies on neutral atomic optical clocks have made remarkable progress.[1–4] An advantage of employing the optical lattice is that the neutral atoms in the lattice could have a much longer interrogation time than in free space. Further, it is realizable to constrain millions of atoms in the subwavelength-size region, which is called the Lamb–Dicke regime.[5] Although the Doppler and photon-recoil effects are greatly suppressed, the electric field of the lattice laser will strongly perturb the energy levels through the alternating current (AC) Stark effect, which is detrimental especially for an atomic optical clock. This issue has been well solved since the far-detuned optical lattice with AC Stark-free wavelength (i.e., magic wavelength) was proposed.[6] The leading differential scalar light shift of the two clock states induced by the lattice laser is cancelled out.[7] In fact, the lattice field having residual nonlinear polarization may give rise to an unwanted vector light shift. Since the optical lattice clock is also susceptible to the collision-induced frequency shift, there are two representative lattice geometries for mainly suppressing these effects. One is the one-dimensional (1D)[8] or two-dimensional (2D)[9] optical lattice embracing spin-polarized fermions. The other one is a three-dimensional (3D) single-occupancy lattice[10] for bosons with the scalar clock states (i.e., $^1S_0$ and $^3P_0$ states). The vector light shift vanishes in both lattice geometries, and the collisional shift is significantly suppressed. Since large ensembles of neutral cold atoms are confined in the optical lattice, the frequency instability of the atomic optical clocks can approach a level of 10^{-16} or below.[11–13]

In this paper, we report on the experiments of ytterbium optical lattices in one, two, and three dimensions, respectively. For each individual case, the atoms are visibly confined in the lattice. The lifetime of the atomic sample held in a 1D optical lattice is investigated. We measure the temperature of in-lattice atoms by the time-of-flight (TOF) method,[14] and the results show that the temperature is similar to that in the green magneto–optical trap (MOT). In addition, the number of atoms in the lattice can be estimated with the fluorescence signal induced by a 399-nm probe laser.

2. Description of the experiment

The optical lattice essentially consists of millions of optical dipole traps,[15] and there is no cooling effect on atoms because the optical dipole trap is a conservative trap deriving from the dipole forces.[16] Usually, the potential depth of the optical lattice applied to the optical clocks is about a few tens of μK. In order to trap more atoms in the optical lattice, the atoms need to be cooled down to the temperature at a level of μK before loading into the lattice. In our experiments, the ^{171}Yb atoms are continuously cooled in the blue and green two-stage MOTs before loading into the optical lattice. The blue MOT using the strong $^1S_0-^1P_1$ transition line at 399 nm is described in our previous work.[17] Here we briefly summarize the most relevant details. The atomic beam effuses from an oven which is heated at a temperature of 773 K. After travelling through two mechanical collimators, the thermal ytterbium beam is further transversely cooled by the 2D optical molasses (2D-OM). Since the capture velocity of the blue MOT is about a few tens of m/s, a Zeeman slower is indispensable for decelerating the longitudinal velocity of the thermal atomic beam with a few hundreds of m/s before the atoms

*Project supported by the National Key Basic Research and Development Program of China (Grant Nos. 2012CB821302 and 2010CB922903), the National Natural Science Foundation of China (Grant Nos. 11134003 and 10774044), and the Shanghai Excellent Academic Leaders Program of China (Grant No. 12XD1402400).

†Corresponding author. E-mail: xyxu@phy.ecnu.edu.cn

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enter into the blue MOT. The Zeeman slower consists of an increasing magnetic field and a 399-nm circularly-polarized light. In the experiments, the longitudinal velocity of the ytterbium atoms is decelerated from ~ 300 m/s to 15 m/s. Finally, about 10^7 of ^{171}Yb atoms are trapped in the blue MOT and cooled to a temperature of about 3 mK.

Immediately after the blue MOT is turned off, the green MOT[18] beams are turned on and the B-field gradient is turned down from 50 Gs/cm to 15 Gs/cm (1 Gs = 10^{-4} T). The cold ^{171}Yb atoms in the blue MOT are transferred into the green MOT for further cooling. Typically, the transfer efficiency of atoms from the blue MOT to the green MOT is about 50%. Since the narrow transition $^1S_0$–$^3P_1$ at 556 nm is utilized in the green MOT, which has a Doppler-limited temperature of 4.4 μK, the temperature of the ^{171}Yb atoms in the green MOT could reach a few tens of μK. Here the 556-nm cooling laser is generated by the second-harmonic-generation (SHG) technique. Instead of using a ring cavity, we employ a single-pass periodically poled $MgO:LiNbO_3$ waveguide for frequency doubling to produce the 556-nm laser light.[19] The infrared light source at 1111.6 nm is produced by a diode laser with a fiber amplifier. The 556-nm laser beams are overlapped with the 399-nm laser beams by use of the dichroic mirrors in three mutual orthogonal directions, two in the horizontal plane and one in the vertical direction, respectively.

As for the odd isotopes like ^{171}Yb, the sub-Doppler cooling takes place and produces a lower temperature than pure Doppler cooling due to their having a nonzero nuclear spin.[20] In this experiment, after two-stage cooling the typical temperature of ^{171}Yb atoms in the green MOT is about 20 μK.

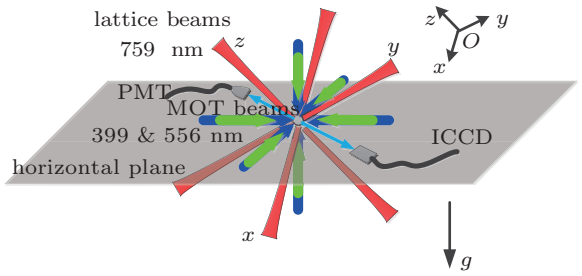


Fig. 1. (color online) Experimental setup for the optical lattice. The blue and green laser beams lying in the horizontal and vertical planes are superposed using the dichroic mirrors. The lattice beams form the so-called "(1, 1, 1)" configuration. The "g" is the local gravity acceleration. The atom cloud is simultaneously imaged onto the intensified charge-coupled device (ICCD) and the photomultiplier tube (PMT).

For the optical lattice, we choose the three orthogonal optical paths with the so-called "(1, 1, 1)" configuration, and there is a pair of counterpropagating laser beams in each path, as shown in Fig. 1. The lattice beam comes from a continuous-wave Ti:sapphire laser with a linewidth of about 75 kHz. The wavelength tuning range is from 700 nm to 1000 nm, which conveniently covers around the magic wavelength of 759 nm for the ytterbium atomic optical clock. The output power is approximately 4 W at 759 nm and divided equally into three beams along the three axes as shown in Fig. 1. The frequencies of the lattice beams in three directions are set to be f_0, $f_0 + 80$ MHz, and $f_0 + 160$ MHz respectively by using three acousto–optic modulators (AOMs), where f_0 is the frequency of the laser output from the Ti:sapphire laser, avoiding the interference between two different-dimensional lattice beams to have the stable 2D or 3D optical lattice. Each laser beam is focused by a lens with a focal length of 12 cm to a waist of about 30 μm. It travels through a second 12 cm lens on the other side of the vacuum chamber, then it is retroreflected. The potential depth is estimated to be $500E_r$ for each dimension, corresponding to a temperature of 50 μK, where $E_r = \hbar^2k^2/2m$ is the photon recoil energy with the reduced Planck constant $\hbar = h/(2\pi)$, the wavevector $k = 2\pi/\lambda$, and the atomic mass m of the ^{171}Yb. In our case, the 2D (3D) lattice potential depth can be estimated as the sum of two (three) superimposed 1D lattice potential depths, i.e., $1000E_r$ for the 2D lattice and $1500E_r$ for the 3D lattice. The realization of trapping atoms in the optical lattice at 759-nm wavelength is more complicated. By careful alignment, the blue MOT beams, green MOT beams, and lattice beams all need to be exactly crossed at the center of the vacuum chamber. Our lattice is similar to the 1D vertical optical lattice,[21] therefore, the tunneling effect[22] between the neighbor sites is strongly reduced, and the residual Doppler and recoil effects can also be reduced below 10^{-17}.[23]

3. Experimental procedure and results

The time sequence for the experiment on the optical lattice is illustrated in Fig. 2. The ytterbium atoms are first cooled in the blue MOT for 1000 ms, then further cooled in the green MOT for 100 ms. At the end of the cooling process, the 1D lattice is switched on for a varied time Δt with the B-field off. In order to observe the atoms in the lattice, the 399-nm MOT beams are on again for 1 ms at the end of the lattice period. The image of the atom clouds is taken by an intensified charge-coupled device (ICCD) and the fluorescence signal is collected with a photomultiplier tube (PMT) as shown in Fig. 1. According to the fluorescence signal, the number of atoms in the lattice can be estimated.

The cold ^{171}Yb atoms trapped in the optical lattice for $\Delta t = 10$ ms, 20 ms, 50 ms, 150 ms, 250 ms, and 350 ms can be observed as shown in Figs. 3(a)–3(f) respectively. In Fig. 3(a), the image of the atomic cloud is taken after the optical lattice has been on for 10 ms, the untrapped cold atomic cloud is fallen down by the gravity, slightly overlapping with the trapped atomic cloud. After $\Delta t = 20$ ms, two atomic clouds are apparently separated in space as shown in Fig. 3(b), showing that most of atoms leave from the lattice, and roughly only a few percent of total atoms in the green MOT are trapped inside the lattice. Since the lattice laser power is limited at a

few Watts and the wavelength of the lattice laser is very far detuned, the lattice beams need to be focused down to a small size to have a high laser intensity and the enough potential depth. Usually, the size of the atomic cloud in the green MOT is about a few hundred microns, and the lattice light is focused to tens of microns. Therefore, a few percent of atoms in the green MOT will be finally trapped in the lattice as shown in Fig. 3(b). Due to the collision between the cold atoms in the lattice and the thermal atoms in the background inside the vacuum chamber, the number of atoms in the lattice will decrease with the lattice holding time as shown in Figs. 3(c)–3(f).

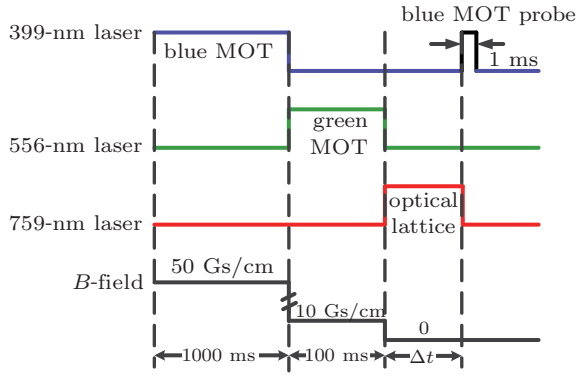


Fig. 2. (color online) Time sequences for the blue and green MOTs, the magnetic field gradient and the optical lattice. The blue MOT light is also used as the probe. Δt can be set to be the value in a range from 50 ms to 350 ms for the lifetime measurement of atoms in the optical lattice.

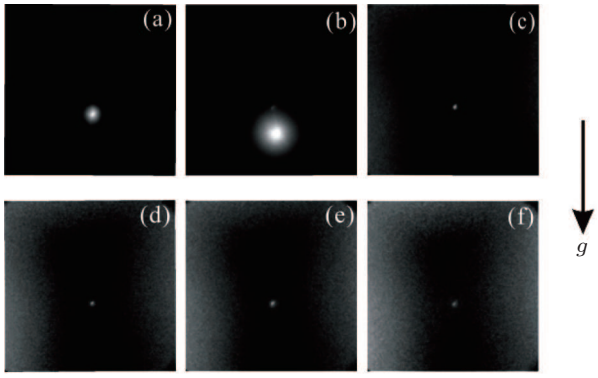


Fig. 3. Images captured by ICCD for various values of Δt: (a) 10 ms, (b) 20 ms, (c) 50 ms, (d) 150 ms, (e) 250 ms, (f) 350 ms.

Figure 4 shows the experimental results of the lifetime measurement of the cold ^{171}Yb atoms in the optical lattice. First, the atoms are trapped in the lattice for a time Δt, then the lattice is turned off while the 399-nm MOT beams are turned on for probing. At the same time, an ICCD exposure is performed. The fluorescence intensity is obtained by extracting the peak value from the ICCD image. By the exponential-decay fitting, the in-lattice $1/e$ lifetime is about 226 ms as shown in Fig. 4, which is mainly limited by the background vacuum pressure at this moment.

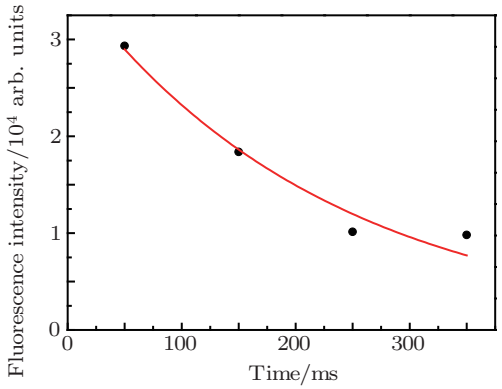


Fig. 4. (color online) Fluorescence intensity of in-lattice atoms versus confinement time. The dots are the measured data, and the solid line is the fitting curve.

We measure the temperature of atoms in the 1D lattice by the TOF technique. First the atoms are held in the lattice for 150 ms, then the lattice laser is turned off, and the atomic cloud falls down under the influence of gravity with free expansion. After a few milliseconds, the 399-nm probe laser is turned on and irradiates on the atomic cloud, and its image is taken by the ICCD. In Fig. 5, the images with various TOF times are shown. From a series of images as shown in Fig. 5, the root-mean-square radii r_i $(i = 1,2)$ at the release times t_i $(i = 1,2)$ are deduced by fitting the fluorescence signal with the Gaussian distribution, respectively. The temperature of the in-lattice atoms can be estimated from $T=(m/2k_{\rm B})\cdot[(r_2^2-r_1^2)/(t_2^2-t_1^2)]$, where $k_{\rm B}$ is the Boltzmann constant. The typical measured-temperature is 32 ± 10 μK, a bit higher than the temperature of the atoms in the green MOT in this case. Ideally, they should be the same through an adiabatic transfer, which means that there are some heating effects within the lattice which will be investigated soon. We note that the atomic cloud in Fig. 5(a) shows a little tailed shape along the lattice direction, which could result from the lattice beam misalignment or intensity imbalance.

By carefully aligning the lattice beams, we can load the ^{171}Yb or ^{174}Yb atoms into the various lattices. As shown in Fig. 6, the ^{171}Yb atoms are successfully loaded into the 1D optical lattice in x, y, and z directions, respectively. Furthermore, the atoms can be loaded into 2D or 3D lattices as shown in Fig. 7. For instance, the 2D lattice along x and z directions can clearly be seen from Fig. 7(a). In Fig. 7(d), the 3D confinement of atoms is also achieved. As shown in Figs. 6(b) and 7(c), the numbers of atoms confined in the 1D optical lattice along the y direction and the 2D optical lattice along the x and y directions are less than those in other lattices, which could be caused by the y-direction lattice beam waist not spatially overlapping with the atomic cloud well. In addition, based on the observed fluorescence signals induced by the 399-nm probe laser, typically, about 10^5 of ^{171}Yb atoms can be loaded into the 1D optical lattices as well as the 10^4 of ^{171}Yb atoms into the multi-dimensional lattices.

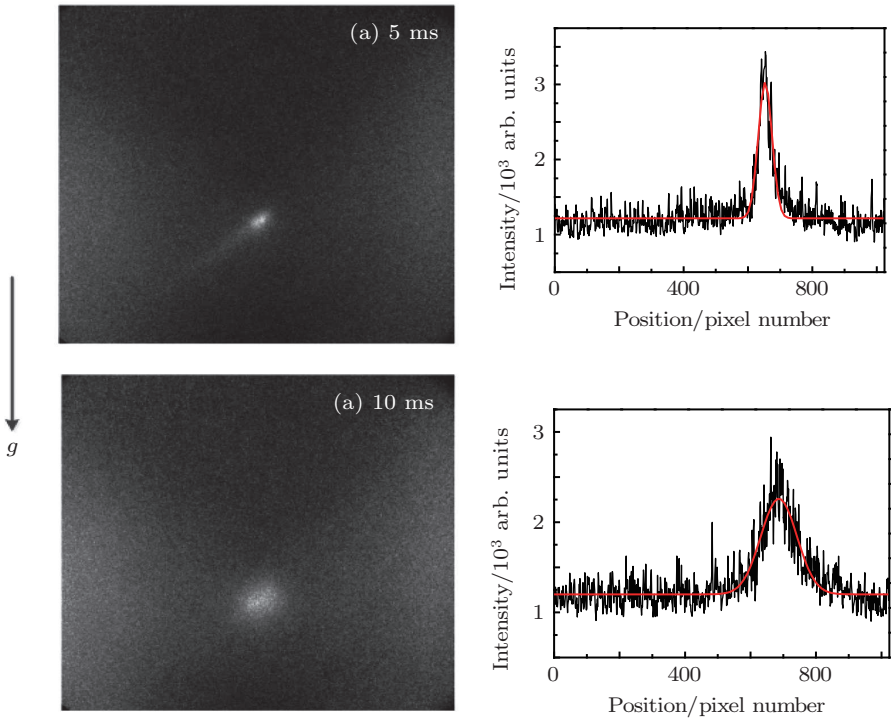


Fig. 5. (color online) TOF images of the in-lattice atoms for various release times (a) $t_1 = 5$ ms, and (b) $t_2 = 10$ ms. By fitting the fluorescence signal with the Gaussian distribution, the temperature of atoms in the optical lattice can be obtained.

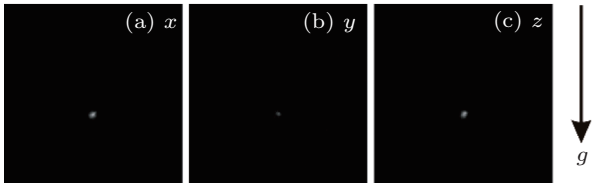


Fig. 6. Images of the atomic cloud in 1D optical lattices along the (a) x direction, (b) y direction, and (c) z direction.

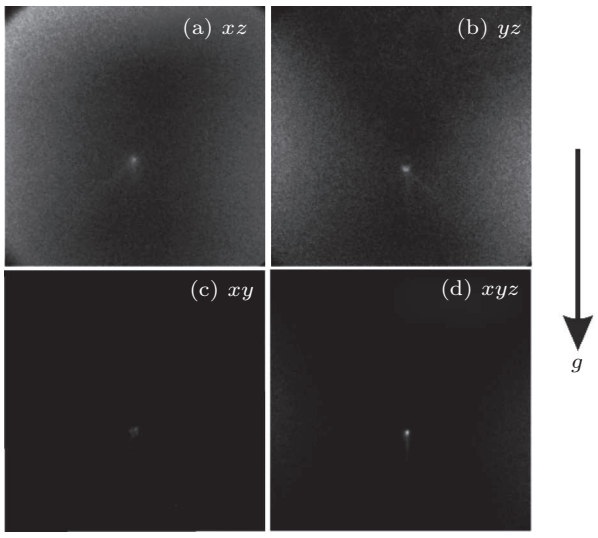


Fig. 7. Images of the atomic cloud in various 2D optical lattices as shown in (a) xz, (b) yz, and (c) xy; and in the 3D optical lattice (d) xyz, respectively.

4. Conclusion

In this paper, we successfully traped more than 10^4 atoms in various optical lattices operating at the 759-nm magic wavelength. Especially for the 1D confinement, the atoms in lattice have a temperature of 32 ± 10 μK with a lifetime of 226 ms, respectively. Recently, the ultracold ^{171}Yb atoms in a 1D lattice have been utilized for developing an ytterbium atomic optical clock. We will apply a 2D optical lattice to a ^{171}Yb optical clock to reduce the frequency shift induced by the cold-atom-collision effect. Furthermore, we are planning to make a ^{174}Yb optical clock with a 3D lattice, so that we can do the frequency comparison between the ^{171}Yb and ^{174}Yb optical clocks.

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