Pulse loading ^{87}Rb Bose-Einstein condensation in optical lattice: the Kapitza-Dirac scattering and temporal matter-wave-dispersion Talbot effect

Haixia Chen (陈海霞), Dezhi Xiong (熊德智), Pengjun Wang (王鹏军), and Jing Zhang (张 靖)*

State Key Laboratory of Quantum Optics and Quantum Optics Devices, Institute of Opto-Electronics, Shanxi University, Taiyuan 030006, China

**E-mail: jzhang74@sxu.edu.cn*

Received June 15, 2009

We study ^{87}Rb Bose-Einstein condensation (BEC) loading into the pulse of the one-dimensional (1D) optical lattice experimentally. The lattice is turned on abruptly, held constant for a variable time, and then turned off abruptly. The measurement of the depth of the optical lattice is obtained by Kapitza-Dirac scattering. The temporal matter-wave-dispersion Talbot effect with ^{87}Rb BEC is observed by applying a pair of pulsed standing waves (as pulsed phase gratings) with the separation of a variable delay.

OCIS codes: 020.1475, 020.0020, 020.1335, 140.3290.

doi: 10.3788/COL20100804.0348.

Bose-Einstein condensation (BEC) was first demonstrated in 1995[1,2], creating an explosion of interest in previously unattainable many-body quantum phenomena. Subsequently, optical lattices[3,4] constitute a natural extension of the experimental efforts to periodic potentials and have opened up new avenues for research. Optical lattices have allowed us to go beyond the physics of a weakly interacting Bose gas and in fact bring the system into a regime where several challenging phenomena of strongly correlated systems of condensed matter physics can be observed. In addition to the fascinating physics of strongly correlated quantum matter, BECs in optical lattice also offer many new possibilities for quantum information processing, especially due to the large size of the quantum registers that can be realized. So far, experiments using periodic potentials have focused mainly on Bragg scattering[5,6] and quantum phase transition properties, involving such intriguing concepts as number squeezing[7] and the Mott insulator transition[8,9]. Some interesting work has also been done on superfluid properties of BECs in optical lattices[10,11].

Coherent manipulation of atomic momentum states is the primary goal of atom optics, and the standing wave light (optical lattice) with associated stimulated light forces is usually used as a primary method of achieving this goal. Bragg scattering is the simplest example of coherent momentum transferring to atoms by the standing wave light. Bragg scattering process requires energy and momentum to be conserved. To avoid Bragg scattering atoms into the wrong final states, the Fourier width of the applied light pulsed with length τ must be smaller than the separation between momentum states $\tau \gg \pi/4\omega_{\rm rec}$, where $\omega_{\rm rec}$ is the recoil frequency. Comparing with the Bragg regime, Kapitza-Dirac (or Raman-Nath) scattering can be treated with $\tau \ll \pi/4\omega_{\rm rec}$, which is limited to short interaction time[12,13]. In this limit, the Fourier width of the pulse is larger than the separation between adjacent momentum states, and atoms can be scattered into higher order momentum states. This is equivalent to that the only effect of the pulse is to impose a spatially periodic phase modulation on the atomic wave function, with no effect on its amplitude profile. In this letter, we report on experiments with BEC loaded into the pulse of one-dimensional (1D) optical lattices. The lattice is turned on abruptly, held constant for a variable time, and then turned off abruptly. In particular, we measure the depths of the optical lattices through Kapitza-Dirac scattering, and then the temporal wave-matter-dispersion Talbot effect, where a pulsed phase grating formed by pulsed optical standing wave is applied to a cloud of BEC, is demonstrated experimentally.

The experiment is performed with a condensate of up to 1×10^5 atoms in the $F = 2, m_F = 2$ state of ^{87}Rb, without a discernible noncondensed component, formed in a quadrupole-Ioffe configuration trap[14] with trapping frequencies of 2×23.9 Hz in the axial and 2×236.6 Hz in the radial direction[15]. The 1D optical lattice is formed by a retro-reflected laser beam along the axial direction whose frequency and amplitude can be controlled by an acousto-optic modulator (AOM). The lattice beam is from a single-frequency diode laser, which passes a standard polarization maintaining single-mode fiber, and has a power of about 8.5 mW. It is detuned about 81 GHz to the red of the D2 line, and is focused into a spot with an intensity full-width at half-maximum (FWHM) of 36 μm. The recoil energy is $E_{\rm rec}/\hbar = 2\pi \times 3.7709$ kHz for ^{87}Rb. The condensate is located in the focus of the lattice beam.

The retro-reflected laser beam forms a standing wave, which acts on the atoms via the light-shift to produce a sinusoidal potential

$$V(x) = V_0 \left[1 + \cos(2k_{\rm L}x)\right], \quad (1)$$

where $2V_0$ is the lattice depth, and $k_{\rm L}$ is the wavenumber of the lattice beam. Given the initial atomic wavefunction $|\psi_0(t=0)\rangle$, the atomic wavefunction immediately after the lattice square wave pulse with time interval Δt is given as[12,13]

1671-7694/2010/040348-03

$$\begin{aligned}\psi(x,t) &= \psi_0 \exp\left[-\frac{\mathrm{i}}{\hbar}\int_0^{\Delta t} \mathrm{d}t V(x,t)\right] \\ &= \psi_0 \exp\left(\frac{-\mathrm{i}V_0\Delta t}{\hbar}\right)\exp\left[-\frac{\mathrm{i}V_0\Delta t}{\hbar}\cos(2k_\mathrm{L}x)\right] \\ &= \psi_0 \exp\left(\frac{-\mathrm{i}V_0\Delta t}{\hbar}\right)\sum_{n=-\infty}^{\infty}(-\mathrm{i})^n \mathrm{J}_n\left(\frac{V_0\Delta t}{\hbar}\right) \\ &\quad\cdot \exp(\mathrm{i}2nk_\mathrm{L}x), \qquad (2)\end{aligned}$$

where J_n is Bessel function. It is shown clearly that the effect of the pulse optical lattice is to impose a spatially periodic phase modulation on the atomic wave function. Thus the BEC breaks up into momentum components with $2n\hbar k_\mathrm{L}$ (n is integer) and the states with momentum of $2n\hbar k_\mathrm{L}$ are populated with probability[16]

$$P_n = \mathrm{J}_n^2\left(\frac{V_0\Delta t}{\hbar}\right). \qquad (3)$$

When the interval time Δt equals 2.4048 $\hbar/V_0$, $\mathrm{J}_0(2.4048) = 0$ and the order $n = 0$ momentum component first vanishes. The lattice depth $2V_0 = 2 \times 2.4048\hbar/\Delta t_0$ can be found by measuring the interval time Δt_0 at which the order $n = 0$ first vanishes.

To measure the lattice depth using the Kapitza-Dirac scattering, the optical lattice is applied to the BEC and we keep it on for a variable length of the interval time Δt, and then the lattices and the trap are simultaneously turned off. After expanding freely for 14 ms time-of-flight (TOF), the relative population of the momentum components is imaged by resonant absorption imaging. The experimental timing sequence is shown in Fig. 1(a). Figure 1(b) shows the time evolution of BEC held in the optical lattices. We measured the atom number of the order $n = 0$. In Fig. 1(c), we plot N_0/N_t (N_t is the total atom number) versus duration time Δt of the optical lattice, and find the $n = 0$ order first vanishes when the lattice duration time Δt_0 is 3 μs. Then the corresponding lattice depth is $67.7E_\mathrm{rec}$. For an atomic polarizability α and a single-beam lattice intensity I, the lattice depth is also given as $2V_0 = \alpha I/(2c\varepsilon_0)$. However, the actual lattice beam power within the glass cell, which mainly determines the effective lattice depth, cannot be measured directly because it is related to the actual beam waist, the lattice beam alignment, and the spatial overlap with the lattice beams. So it is necessary to measure the depths of the optical lattices experimentally. The procedure for measurement of optical lattices can also be used to judge the alignment of the optical lattices with respect to the BEC.

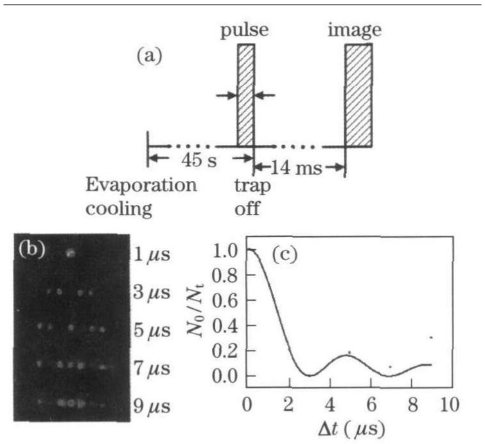

Fig. 1. (a) Experimental timing sequence; (b) TOF images of Kapitza-Dirac scattering as a function of lattice duration time Δt; (c) scattering ratio for the scattering order $n = 0$. The data are fitted with $\mathrm{J}_0^2(at)$, with fitting parameter $a = 0.8$.

We subsequently investigate the temporal matter-wave-dispersion Talbot effect. The Talbot effect has been studied extensively[17,18]. In the atom optics, where light waves are replaced by matter waves, Talbot effect that periodic reconstruction of the matter-wave front occurs at multiples of the Talbot distance L_T in the paraxial approximation has been first demonstrated in 1995[19]. The temporal atom optical Talbot effect in the sodium BEC using a standing wave light grating has been demonstrated[20], for which a pulsed standing wave was applied to BEC in the Kapitza-Dirac scattering regime. The self-imaging of the grating was measured with a second standing wave light grating pulse. We will show that the matter-wave front is reconstructed temporally at multiples of L_T when a pulsed phase grating formed by pulsed optical standing wave is applied to ^{87}Rb BEC. In experiment, the phase grating with periodicity $d = \lambda_\mathrm{L}/2$ is formed by a standing wave of light with wavelength λ_L, and ^{87}Rb BEC is the ultimate coherent atomic source. The Talbot time can be defined as $T_\mathrm{T} = L_\mathrm{T}/v = 2d^2/(\lambda_\mathrm{L}v)$, where v is the atomic velocity. According to the dispersion relation of matter wave $E_n = 4n^2E_\mathrm{rec}$, the Talbot time can be rewritten as $T_\mathrm{T} = 2\pi\hbar/(4E_\mathrm{rec})$. So $T_\mathrm{T} = 66$ μs for ^{87}Rb.

The experimental sequence for the temporal matter-wave Talbot effect is shown in Fig. 2(a). A pair of pulsed standing waves (as phase gratings) separated by a variable delay time T is applied to BEC, then the standing wave and the magnetic trap are simultaneously turned off. The duration time of the two pulsed standing waves is 300 ns. Owing to the small momentum spread of the BEC and short pulse time, the system is in the Kapitza-Dirac scattering regime. The atoms are diffracted into momentum states $2n\hbar k_\mathrm{L}$, after application of the first pulsed grating. According to Eq. (2), the atomic wavefunction immediately after the first pulse at $t = 0$ can be written as

$$\psi(x,t=0^+) = \psi(x,t=0^-) \cdot \sum_{n=-\infty}^{\infty} A_n(t=0^+)\exp(\mathrm{i}2nk_\mathrm{L}x), \qquad (4)$$

where $\psi(x,t=0^-)$ is the atomic wavefunction before the first pulse lattice, and $A_n(t=0^+) = \exp(\frac{-\mathrm{i}V_0\Delta t}{\hbar})(-\mathrm{i})^n\mathrm{J}_n(\frac{V_0\Delta t}{\hbar})$. After the first pulse, the atomic wavefunction evolves freely. So each diffracted momentum state acquires the phases during the evolution as $\exp(-\mathrm{i}E_nt/\hbar)$ ($E_n = 2\pi n^2\hbar/T_\mathrm{T}$). The wavefunction ($t > 0$) can be expressed as

$$\psi(x,t) = \psi(x,t=0^-)\sum_{n=-\infty}^{\infty}\Big[A_n(t=0^+) \exp(\mathrm{i}2nk_\mathrm{L}x)\exp(-\mathrm{i}2\pi n^2 t/T_\mathrm{T})\Big]. \qquad (5)$$

It is apparent that the wave front can be reconstructed temporally at multiple of $T_{\rm T}$, i.e., $\psi(x.t = lT_{\rm T}) = \psi(x, t = 0^+)$ (l is a positive integer).

In order to analyze the temporal evolution of the wavefunction and observe the Talbot effect, a second pulsed standing wave after a delay time T is applied. Figure 2(b) shows images resulting from two pulses for various pulse internal time T. We can find that the images are located symmetrically about $T = 33$ μs, and the image at $T = 66$ μs is the replica of the image at $T = 1$ μs, indicating the wave matter front is reconstructed at the Talbot time. The phenomena that all diffraction orders disappear at $T = 33$ μs can also be found in Fig. 2(b), which can be easily explained. For the case when $T = T_{\rm T}/2$, the wavefunction using Eq. (5) can be written as

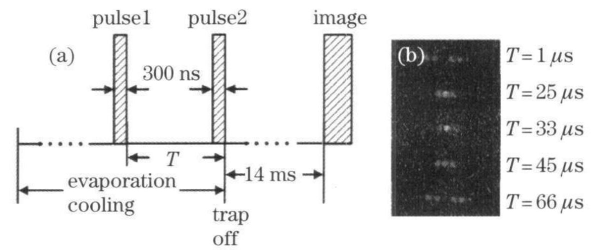

Fig. 2. (a) Experimental timing sequence for the temporal matter-wave Talbot effect. (b) TOF images of BEC resulting from a pair of pulsed gratings with various time delays between pulses.

$$\psi(x,t) = \psi_0 \exp\left(\frac{-{\rm i}V_0\Delta t}{\hbar}\right) \sum_{n=-\infty}^{\infty} \left[(-{\rm i})^n {\rm J}_n\left(\frac{V_0\Delta t}{\hbar}\right) \exp({\rm i}2nk_{\rm L}x) \exp\left(-{\rm i}\pi n^2\right)\right]$$
$$= \psi_0 \exp\left(\frac{-{\rm i}V_0\Delta t}{\hbar}\right) \sum_{n=-\infty}^{\infty} {\rm i}^n {\rm J}_n\left(\frac{V_0\Delta t}{\hbar}\right) \exp({\rm i}2nk_{\rm L}x) = \psi_0 \exp\left(\frac{-{\rm i}V_0\Delta t}{\hbar}\right) \exp\left[\frac{{\rm i}V_0\Delta t}{\hbar}\cos(2k_{\rm L}x)\right]. \quad (6)$$

The atomic wavefunction at $T = T_{\rm T}/2$ is just like that the potential of the pulse lattice with $V(x) = V_0[1 - \cos(2k_{\rm L}x)]$ acts on the original atomic wavefunction. Therefore the effect of the second pulse at $T = T_{\rm T}/2$ cancels the spatial variation produced by the first pulse grating, resulting in the disappearance of the all diffraction orders.

In conclusion, we use Kapitza-Dirac scattering as an accurate way to calibrate the lattices depth. We also demonstrate the temporal matter-wave-dispersion Talbot effect by applying a pair of pulsed phase gratings to a Rb BEC. These works will be helpful for our future work of manipulating the Bose-Fermi mixture gas by optical lattices.

This work was supported in part by the National Natural Science Foundation of China for Distinguished Young Scholars (No. 10725416), the National Basic Research Program of China (No. 2006CB921101), the National Natural Science Foundation of China for Excellent Research Team (No. 60821004), and the National Natural Science Foundation of China (No. 60678029).

References

1. M. H. Anderson, J. R. Ensher, M. R. Matthews, C. E. Wieman, and E. A. Cornell, Science **269,** 198 (1995).
2. K. B. Davis, M.-O. Mewes, M. R. Andrews, N. J. van Druten, D. S. Durfee, D. M. Kurn, and W. Ketterle, Phys. Rev. Lett. **75,** 3969 (1995).
3. P. S. Jessen and I. H. Deutsch, Adv. At. Mol. Opt. Phys. **37,** 95 (1996).
4. L. Qi, Z. Yang, X. Gao, and Z. Liang, Chin. Opt. Lett. **6,** 279 (2008).
5. M. Kozuma, L. Deng, E. W. Hagley, J. Wen, R. Lutwak, K. Helmerson, S. L. Rolston, and W. D. Phillips, Phys. Rev. Lett. **82,** 871 (1999).
6. D. M. Stamper-Kurn, A. P. Chikkatur, A. Görlitz, S. Inouye, S. Gupta, D. E. Pritchard, and W. Ketterle, Phys. Rev. Lett. **83,** 2876 (1999).
7. C. Orzel, A. K. Tuchman, M. L. Fenselau, M. Yasuda, and M. A. Kasevich, Science **291,** 2386 (2001).
8. M. Greiner, O. Mandel, T. Esslinger, T. W. Hansch, and I. Bloch, Nature **415,** 39 (2002).
9. D. Jaksch, C. Bruder, J. I. Cirac, C. W. Gardiner, and P. Zoller, Phys. Rev. Lett. **81,** 3108 (1998).
10. S. Burger, F. S. Cataliotti, C. Fort, F. Minardi, and M. Inguscio, Phys. Rev. Lett. **86,** 4447 (2001).
11. F. S. Cataliotti, S. Burger, C. Fort, P. Maddaloni, F. Minardi, A. Trombettoni, A. Smerzi, and M. Inguscio, Science **293,** 843 (2001).
12. G. K. Campbell, "^{87}Rubidium Bose-Einstein condensates in optical lattices", PhD. Thesis (Massachusetts Institute of Technology, 2006).
13. S. Gupta, A. E. Leanhardt, A. D. Cronin, and D. E. Pritchard, C. R. Acad. Sci. **2,** 479 (2001).
14. D. Xiong, H. Chen, P. Wang, X. Yu, F. Gao, and J. Zhang, Chin. Phys. Lett. **25,** 843 (2008).
15. P. J. Wang, H. X. Chen, D. Z. Xiong, X. D. Yu, F. Gao, and J. Zhang, Acta Phys. Sin. (in Chinese) **57,** 4840 (2008).
16. Y. B. Ovchinnikov, J. H. Müller, M. R. Doery, E. J. D. Vredenbregt, K. Helmerson, S. L. Rolston, and W. D. Phillips, Phys. Rev. Lett. **83,** 284 (1999).
17. K. Banaszek and K. Wodkiewicz, Opt. Express **2,** 169 (1998).
18. M. V. Berry and E. Bodenschatz, J. Mod. Opt. **46,** 2139 (1999).
19. M. S. Chapman, C. R. Ekstrom, T. D. Hammond, J. Schmiedmayer, B. E. Tannian, S. Wehinger, and D. E. Pritchard, Phys. Rev. A **51,** R14 (1995).
20. L. Deng, E. W. Hagley, J. Denschlag, J. E. Simsarian, M. Edwards, C. W. Clark, K. Helmerson, S. L. Rolston, and W. D. Phillips, Phys. Rev. Lett. **83,** 5407 (1999).