CHIN. PHYS. LETT. Vol. 35, No. 6 (2018) 063201

Influence on the Lifetime of ^{87}Rb Bose–Einstein Condensation for Far-Detuning Single-Frequency Lasers with Different Phase Noises *

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(Received 18 February 2018)

We study the influence of the phase noises of far detuning single frequency lasers on the lifetime of Bose–Einstein condensation (BEC) of ^{87}Rb in an optical dipole trap. As a comparison, we shine a continuous-wave single-frequency Ti:sapphire laser, an external-cavity diode laser and a phase-locked diode laser on BEC. We measure the heating and lifetime of BEC in two different hyperfine states: $|F=2, m_F=2\rangle$ and $|F=1, m_F=1\rangle$. Due to the narrow linewidth and small phase noise, the continuous-wave single-frequency Ti:sapphire laser has less influence on the lifetime of ^{87}Rb BEC than the external-cavity diode laser. To reduce the phase noise of the external-cavity diode laser, we use an optical phase-locked loop for the external-cavity diode laser to be locked on a Ti:sapphire laser. The lifetime of BEC is increased when applying the phase-locked diode laser in contrast with the external-cavity diode laser.

PACS: *32.70.Cs*, *03.75.Nt*, *67.85.Jk* DOI: 10.1088/0256-307X/35/6/063201

With the development of laser technology, researchers can realize the fifth state of matter: Bose–Einstein condensation (BEC).[1,2] Ultracold atoms have become an ideal experimental platform for investigating condensed matter physics[3] and providing versatile applications in quantum optics and quantum information processing.[4] Researchers are continuously performing extensive and deep research on ultracold atoms, both theoretically and experimentally, and finding many new phenomena. In recent years, one-dimensional spin-orbit coupling (SOC) in bosons[5–9] and fermions[10–14] was realized experimentally by using a pair of counter-propagating Raman lasers to dress two atomic spin states. The generated SOC represents a sum of Rashba $\alpha(\sigma_x k_y - \sigma_y k_x)$ and Dresselhaus $\beta(\sigma_x k_y + \sigma_y k_x)$,[15,16] which attracted great attention in quantum simulation. SOC plays a key role in many exotic topological materials. Recently, two-dimensional SOC was realized in fermions by coupling three internal spin states of ultracold ^{40}K Fermi gases through three Raman lasers propagating in a plane,[17,18] which was also realized in BEC using a Raman lattice.[19]

In our experiment, a tunable continuous-wave single-frequency Ti:sapphire laser is used to generate a pair of Raman lasers for SOC. The heating effect due to the lasers is the key problem in SOC. In this study, we focus on the heating effect on BEC with only one laser beam. As a comparison, a continuous-wave single-frequency Ti:sapphire laser, an external-cavity diode laser and a phase-locked diode laser are applied on BEC, respectively. We check the influence of the phase noises of the different kinds of the far-detuning single-frequency lasers on the lifetime of BEC. The work will help us to realize which kind of laser should be chosen for the Raman coupling in experiments.

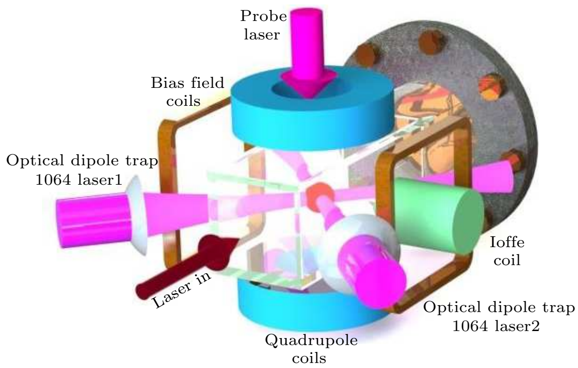

Fig. 1. Schematic diagram of the experimental setup. BEC is obtained in a crossed optical dipole trap. A single far-detuning laser beam is applied on the BEC.

Our experimental setup is shown in Fig. 1. The preparation of the ^{87}Rb BEC has been described in detail in previous work.[20–23] The ^{87}Rb atoms are optically cooled and trapped in magneto-optical trap (MOT), then transferred to the magnetic trap with the quadrupole-Ioffe configuration (QUIC) where atoms are precooled to 1.5 μK by rf-induced evapora-

*Supported by the National Key Research and Development Program of China under Grant Nos 2016YFA0301600 and 2016YFA0301602, the National Natural Science Foundation of China under Grant Nos 11234008, 11474188 and 11704234, and the Fund for Shanxi '1331 Project' Key Subjects Construction.

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tion. Then, atoms are transferred to the center of the cell by decompressing the QUIC trap, where the atoms are further cooled to obtain BEC in optical dipole trap. The optical-dipole trap is composed of two horizontal crossed beams at 90° with wavelength of 1064 nm.[20,21] The two beams overlap at the focus and coincide exactly with the cloud of atoms. One beam was focused to a waist size of 38 µm by an achromatic lens with a focus length of 300 mm, and the other beam was focused to 49 µm by a 400 mm lens. The powers of the two optical dipole trap beams after the polarization maintaining single-mode fibers are 1 W and 2 W, respectively. We measure the atom number and temperature by taking an absorption image after 30 ms of expansion. Lastly, we can obtain the ^{87}Rb BEC of 5×10^5 atoms in hyperfine state $|2,2\rangle$ and 2×10^5 ^{87}Rb BEC atoms in hyperfine state $|1,1\rangle$ via a rapid adiabatic passage induced by a microwave frequency.

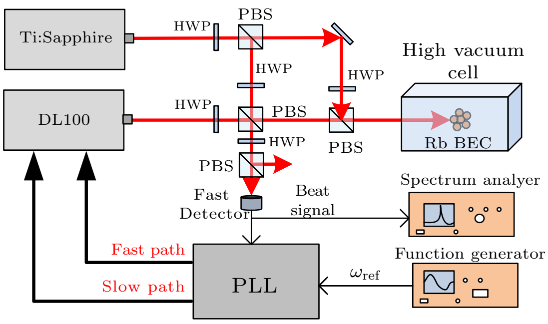

Fig. 2. Schematic diagram. The Ti:sapphire laser and the external-cavity diode laser are mixed at a polarization beam splitter (PBS) and make the polarization same through a combination of half wave plate (HWP) and PBS. Then the mixed laser is focused onto a fast photodiode. The generated beat signal and the reference signal $\omega_{\rm ref}$ is sent into the phase-locked loop circuit. We applied the HWP to adjust the polarization. The laser beam shines from the front panel of the high vacuum cell into the atom cloud.

The single-frequency lasers used here are a tunable continuous-wave single-frequency Ti:sapphire lasers (M squared lasers Ltd; Sols Ti:sapphire) and an external-cavity diode laser (Toptica diode laser DL100). The external-cavity diode laser uses a Littrow configuration to reach an intrinsic linewidth of a few 100 kHz with large phase noises. To reduce the phase noise of the external-cavity diode laser, we use an optical phase-locked loop (PLL) for the external-cavity diode laser to be locked on a Ti:sapphire laser. The optical PLL, which produces phase-coherent lasers, has led to important advances in coherent optical communications, precision spectroscopy, frequency stabilization of lasers, and heterodyne and homodyne detection. Especially, this technology has an important application in the field of atomic physics and quantum optics for the generation of coherently prepared media, such as for EIT and the Raman coupling. The optical PLL has been studied in our previous work.[24] The Ti:sapphire laser and the external-cavity diode laser are mixed at a beam splitter and then focused onto a fast photodiode. The generated beat signal and the reference signal from a function generator are sent into the PLL circuit. The PLL produces the error signal for the diode laser. The PLL has two feedback paths: the fast feedback path and the slow feedback path as shown in Fig. 2. The slow feedback path is applied on a piezoelectric actuator that tilts the diffraction grating of the external-cavity diode laser. The modulation bandwidth of slow feedback path is approximately a few kHz, which is capable of compensating for slow-frequency fluctuation and drifts. The fast feedback path modulates the injection current of the laser diode and the modulation bandwidth is about a few MHz. If only the slow feedback path is applied, the frequency of the external-cavity diode laser follows that of the Ti:sapphire laser. However, the beat signal between the two laser beams is still broad at a few MHz as shown in Fig. 3(a). This means that the phase noise of the external-cavity diode laser is not reduced. To eliminate the phase noise, we add a fast feedback path simultaneously, then the beat frequency signal of two laser beams becomes narrower at about a few Hz as shown in Fig. 3(b), while its two wings still have large noise. This means that the phase noise of the external-cavity diode laser is reduced significantly.

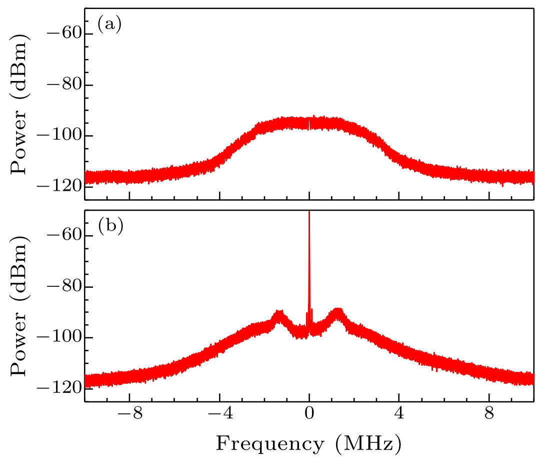

Fig. 3. The spectrum of the beat signal of two lasers, where the span is 20 MHz, and the RBW is 150 Hz. (a) Only the slow feedback path is applied. (b) The fast and slow feedback paths are applied simultaneously.

We apply single Gaussian fitting of the optical density of the atom cloud obtained from the absorption imaging. Then we obtain the Gaussian radius σ of the fitting parameters. Gaussian radius indicates the temperature change. We utilize the time evolution of the atom number and momentum distribution Gaussian radius to study the influence of laser light on the lifetime and heating effect of BEC. Firstly, we prepared the hyperfine state $|2,2\rangle$, and then measured the lifetime of BEC $|2,2\rangle$ in the optical dipole trap.

The differential equation for the atom number in optical trap can be expressed as

$$\dot{N} = -\alpha N - L_3\langle n^2\rangle N, \tag{1}$$

where the loss rate α for the background gas collisions and laser-induced heating, and the three-body loss rate $L_3\langle n^2\rangle$ are considered,[25] L_3 is the three-body loss coefficient, and $\langle n^2\rangle$ is the mean density square. Three-body recombination leads to anti-evaporation atom heating and predominantly happens in the region where the density is the highest in the trap center. Here we only consider the loss rate for the background gas collisions and laser-induced heating, since the three-body loss gives the small contribution in this work. We obtain the lifetime of BEC in optical trap with 3.2 s as shown in Fig. 4(a).

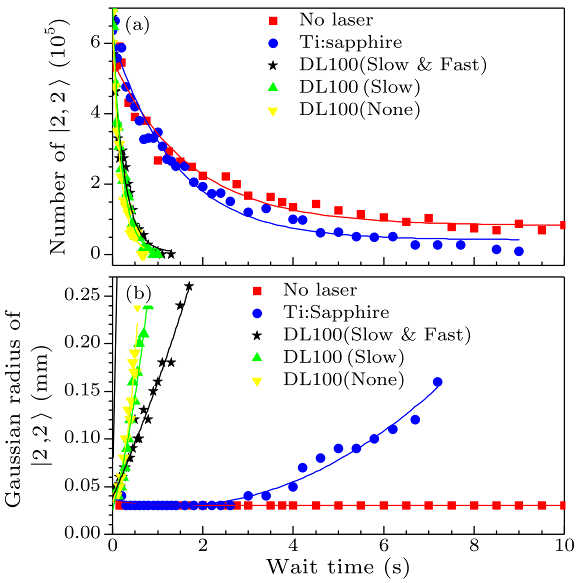

Fig. 4. The atom number (a) and Gaussian radius (b) of the atom cloud versus the holding time in the optical trap with shining the extra laser. BEC is prepared in the $|2,2\rangle$ state, and the power of all the lasers is 15 mW. Red: no extra laser; blue: Ti:sapphire laser; yellow: free-running diode laser; green: diode laser with only an slow feedback path applied; and black: diode laser with fast feedback and slow feedback paths. The point is the experimental data, and the curve is the data fitting result in the single exponential decay function form. It can be expressed as $y = Ae^{\frac{x}{t_0}} + y_0$, where t_0 is the mean lifetime.

We use a Ti:sapphire laser with the wavelength of 785 nm and a waist size of 200 μm to shine the ^{87}Rb BEC. The lifetime and Gaussian radius of the atom cloud are measured as a function of the holding time in the optical trap with shining the Ti:sapphire laser. We can see that the heating effect and the lifetime decrease slightly, as shown in Fig. 4(a) (blue line). Then we replace the Ti:sapphire laser with the external-cavity diode laser. We measure three cases of the external-cavity diode laser: the free-running external-cavity diode laser, only with the slow feedback path, and with the fast and slow feedback paths. Because of the larger amplitude and phase noise of the free running external-cavity diode laser, the lifetime of BEC becomes dramatically shorter at 190 ms and the heating effect becomes significantly serious, as shown in Fig. 4(a) (yellow line). When applying the slow feedback path on the external-cavity diode laser, the lifetime of BEC is almost the same as the free-running external-cavity diode laser. The slow feedback only compensates for the slow-frequency fluctuation and drifts of the diode laser; it does not alter the phase noise. When applying the slow and fast feedback paths simultaneously on the external-cavity diode laser, the lifetime of BEC is improved and the heating effect is reduced, but it is still worse than that of shining the Ti:sapphire laser. Moreover, as comparison, we also measure BEC at the $|1,1\rangle$ state and obtain the similar results as shown in Fig. 5. The lifetime of BEC at the $|1,1\rangle$ state is longer than that of the $|2,2\rangle$ state under the same condition.

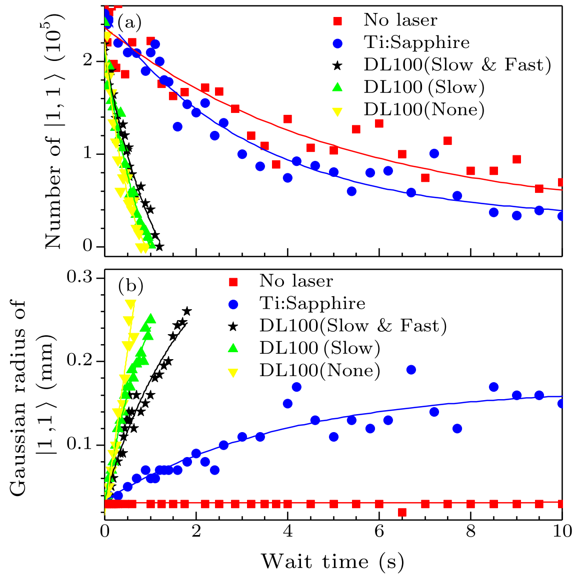

Fig. 5. The atom number (a) and Gaussian radius (b) of the atom cloud as a function of the holding time in the optical trap with shining the extra laser. BEC is prepared in the $|1,1\rangle$ state and the power of all the lasers is 15 mW. Red: no extra laser; blue: Ti:sapphire laser; yellow: free-running diode laser; green: diode laser with only an slow feedback path applied; and black: diode laser with fast feedback and slow feedback paths.

From the above results, we obtain that the phase noise of a far-detuning single-frequency laser can result in a serious heat effect. In the SOC experiment, two or more lasers are used for the two-photon Raman process. Thus if the lasers have larger phase noise, it will lead to serious atom loss due to the heat effect. It will directly influence the BEC of SOC. In brief, the choice of laser source is very important for SOC.

In conclusion, we have measured the lifetime and temperature of ^{87}Rb BEC in an optical dipole trap irradiated by different kinds of far-detuning single-frequency lasers at 785 nm. The single-frequency Ti:sapphire laser has less influence on the ^{87}Rb BEC because of its narrow linewidth and less amplitude-phase noise, while the external-cavity diode laser has a greater influence on the ^{87}Rb BEC due to the larger linewidth and amplitude-phase noise. We use PLL to lock the diode laser on the Ti:sapphire laser with two kinds of conditions: (1) with a slow feedback path only, (2) with slow and fast feedback paths simultaneously. We then obtain a better result than with the unlocked external-cavity diode laser. The experimental results provide a reference for choosing a single-frequency laser to interact with BEC in future ultracold atom experiments.

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