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Simple and robust method for rapid cooling of ^{87}Rb to quantum degeneracy*

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We demonstrate a simple and fast way to produce ^{87}Rb Bose–Einstein condensates. A digital optical phase lock loop (OPLL) board is introduced to lock and adjust the frequency of the trap laser, which simplifies the optical design and improves the experimental efficiency. We collect atoms in a magneto-optical trap, then compress the cloud and cut off hot atoms by rf knife in a magnetic quadrupole trap. The atom clouds are then transferred into a spatially mode-matched optical dipole trap by lowering the quadrupole field gradient. Our system reliably produces a condensate with 2×10^6 atoms every 7.5 s. The compact optical design and rapid preparation speed of our system will open the gate for mobile quantum sensing.

Keywords: optical phase lock loop, laser cooling, Bose–Einstein condensates

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1. Introduction

Preparation of degenerate atomic quantum gases is an important tool for studying their fundamental properties[1–4] or their applications in atomic inertial sensors[5] and gravimeters,[6] as well as in microgravity.[7] A simple and robust method for the generation of Bose–Einstein condensates (BECs) with decent particle number and repetition rate could pave the way for a new generation of atom-based quantum sensors.[8,9]

A range of techniques have been developed to produce BECs but with varying degrees of complexity and difficulty. Magnetic trap is a classical method for making BEC. This kind of traps has large trap volumes, which can be well matched to the size of laser-cooled atom clouds. The effectively linear potential provides tight confinement, allowing for efficient evaporative cooling. However, this method normally takes tens of seconds to minutes to prepare BECs. Using optical dipole trap to achieve quantum degeneracy has been successfully implemented in ultracold atom experiments.[10–14] The tight confinement of optical trap allows for fast evaporation ramps and therefore a cycling time of only a few seconds. However, with this method it is necessary to start evaporative cooling with a large collision rate. As the optical trap volumes are relatively small, the atom number of the condensates is normally on the order of 10^4–10^5.

In this paper, we present a fast and robust method to create a pure BEC of 2×10^6 ^{87}Rb atoms with a repetition time of 7.5 s. An optical phase lock loop (OPLL) board is introduced to adjust the frequency of the trap laser, which simplifies the optical design and improves the experimental efficiency. The main approach is to first load laser-cooled atoms into a magnetic quadrupole trap, then compress the atom clouds and use a forced rf knife to cut off the hot atoms, finally transfer the atoms from the quadrupole trap to a crossed optical dipole trap. With the quadrupole trap compression process, the atom cloud is trapped in the magnetic center of the vacuum cell, so that the two dipole beams also align with the center of the magnetic field. When the optical system misaligned due to vibration and other reasons, we only need to increase the 3D MOT current, and then adjust the dipole beams to overlap with the magnetic field center, which is simple and robust. Compared to the all optical method, our configuration maintains the hardware equipment with benefits of a large optical access, and the atom number of condensates has been increased by an order of magnitude without increasing the preparation time. Finally, this technique is experimentally simple and can be implemented with the same optical access as the optical dipole trap (ODT). It requires only a relatively stronger current supply to produce the quadrupole trap.

2. Experimental apparatus

The primary components of our experiment are a single set of low current (∼15 A) coils that can be dynamically configured to produce either a Helmholtz or a quadruple configuration magnetic field, and two separate 20 W laser beams that cross with large (∼100 μm) waists near the center of the two coils. This simplified system has the advantages of providing

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an improved optical access and maintaining a higher stability and repeatability in the condensate number.

A clean vacuum environment is essential for the experiments with BECs. A schematic of our vacuum system is shown in Fig. 1. The basic optical design of the experiment has been retained as well, utilizing a 2D-magneto-optical trap (2DMOT) to load the primary 3DMOT via a near resonance push beam. The 2D and 3D MOTs are collected in two rectangular 30 mm × 30 mm × 100 mm quartz glass cells on opposite sides of a hollow stainless-steel cube. After initial evacuation of the chamber using a turbomolecular pump, ultra-high vacuum (UHV) is maintained by a 75 L/s ion pump and a titanium sublimation pump (TSP) housed in a 6-inch tube. An electrical feedthrough provides current to two 50 mg rubidium dispensers mounted in the 2D MOT cell, which runs continuously at 3 A. The pressure in the science cell is 1.1×10^{-11} Torr, which is monitored by the ion pump controller.

The laser beams used for the MOTs and for absorption imaging of the atom clouds are derived from two home-built external cavity diode lasers (ECDLs), running at about 60 mW (post isolator). The repump laser works as the master laser, locked at $|F = 1\rangle \rightarrow |F' = 2\rangle$ using saturated absorption spectroscopy (SAS). The slave laser (trap laser) is locked to the master laser by the optical phase lock loop (OPLL) as described in our previous work,[15] locked near the ^{87}Rb $|F = 2\rangle \rightarrow |F' = 3\rangle$ transition, and the frequency difference between the repump laser and the trap laser is around 6.8 GHz.

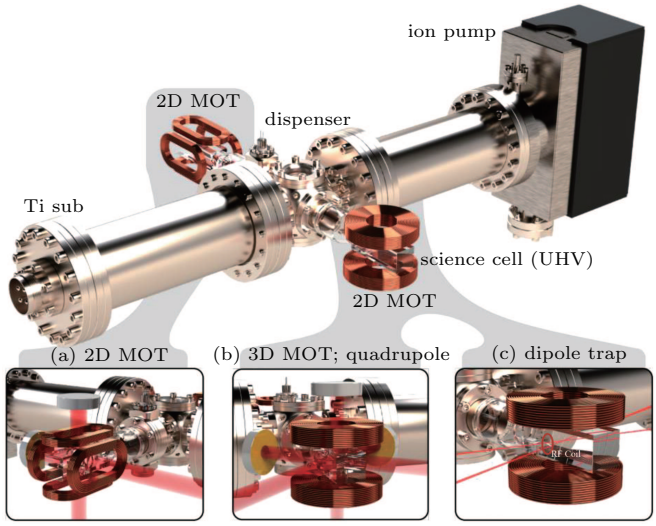


Fig. 1. Diagram of the vacuum system and various key components.

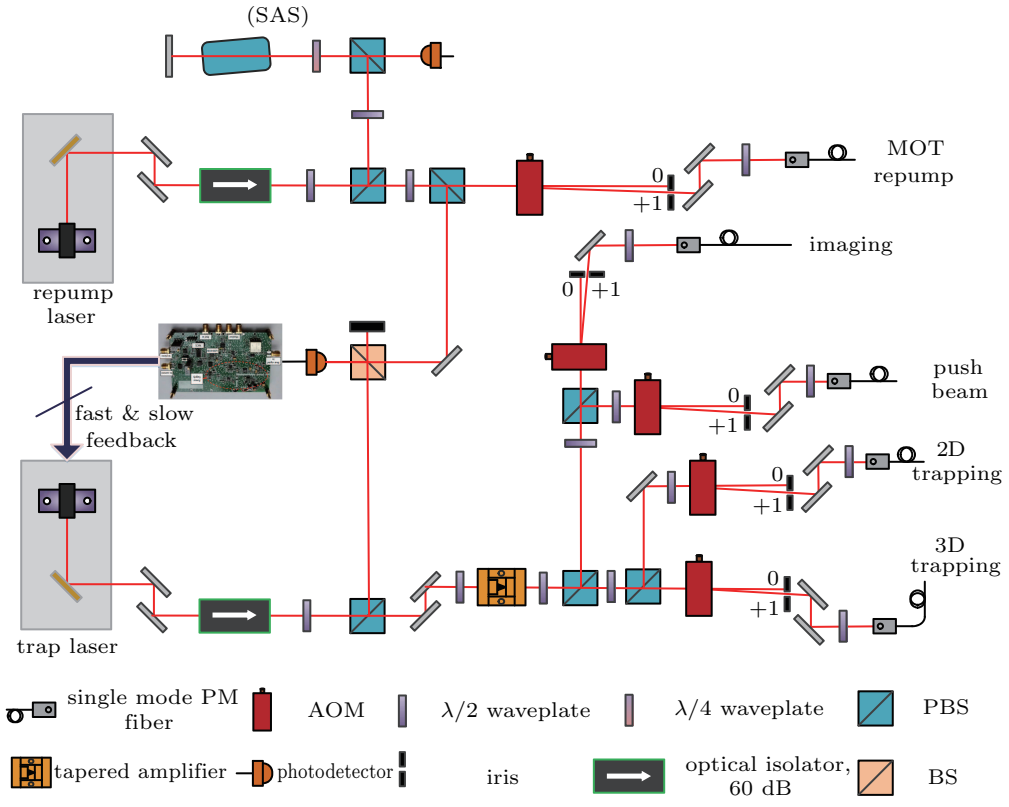


Fig. 2. Optical setup for the 2D and 3D MOTs.

The trap laser is amplified using a tapered amplifier (TA) to increase the power, then the light is split into four parts via three polarization beam splitters (PBS), which are used for the imaging beam, push beam, 2D trapping beam and 3D trapping beam, respectively. All the beams pass through single-pass acoustic-optic modulators (SP AOM), resulting in about 240 mW of trapping light, 1 mW of imaging light and 1 mW of push light to the glass cell after fiber coupling. The re-

pump laser passes through an SAS and an SP AOM, the first order diffracted light is then fiber coupled to the glass cell with a total power of 30 mW for 2D and 3D MOTs. The laser light is guided to the experiment in single-mode polarization-maintaining optical fibers, which serves for mode-cleaning of the beam and allows us to separate the laser table from the main apparatus. Fiber guiding also makes the optical alignment on the BEC table independent of the laser table, which is very useful when making changes to the laser setup.

The 2DMOT beams and push beam are turned off when 3DMOT loading is completed. The detuning of the 3D cooling light is adjusted by OPLL, and then jump back near the resonance frequency of the image light after PGC. In our experiments, the laser frequency adjustment is achieved through OPLL, and AOMs are only used for optical switches. Our optical design, on the one hand, saves space and makes the optical setup simpler. On the other hand, only SP AOM is used, so that more power goes to the glass cell, improving the experimental efficiency. As the OPLL can change the detuning by more than 2 GHz, non-destructive far-detuned shadowgraph imaging of BEC can also be setup in our system to make continuous imaging,[16] which will effectively improve the experimental run cycles, allowing for quantum resources to be probed multiple times in a single experimental run.

3. Experimental results and discussion

Our experiment starts with a 3D MOT capturing approximately 10^9 atoms in 2 s. After atoms are trapped and cooled in the MOT they are still too hot to be loaded into an optical dipole trap. It is necessary to cool them down further using polarization gradient cooling (PGC). In this process, the magnetic field is switched off and the trapping light is detuned smoothly over 15 ms using a linear ramp from 20 MHz to 100 MHz. The intensity of the light is decreased linearly as well by controlling the driving power of the AOM. The intensity of the repump light is reduced during this ramp, to limit the population in the $F = 2$ ground state and to increase the cooling effect of the PGC. With the OPLL setup, the intensity and detuning of the trapping light could be controlled independently, and we can also give more detuning compared with an AOM, which get a better optimization about the PGC. In our system, there are 10^9 atoms at about 12 μK after free space PGC.

Effective evaporative cooling not only requires that the atoms maintain a high elastic collision rate, but also requires that the lifetime of the magnetic trap as long as possible. There are two main sources of atomic loss in the trap, one is the collision of background gas particles, and the other is the residual light heating of the atomic group. Since our experiment uses 2D MOT, 3D MOT, and differential diversion tubes, the background Rb in the 3D MOT is relatively small. The first influencing factor can be ignored. The main factor affecting the lifetime of our magnetic trap is the effect of residual light.

Figure 3 shows the imaging results of the atom cloud with and without the mechanical switch added before the MOT light enters the glass cell. The trap time of the atom cloud in the magnetic trap is 5 s. The atom numbers in Figs. 3(a) and 3(b) are 3.1×10^8 and 1.1×10^8, respectively.

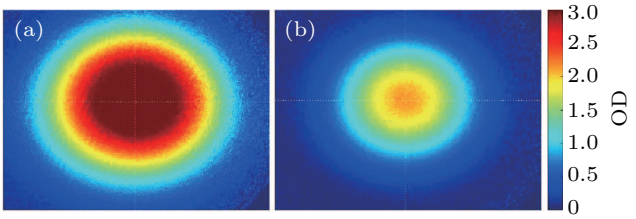


Fig. 3. Imaging of the atom cloud after loading into the quadrupole magnetic trap for 5 s. The atom number is (a) 3.1×10^8 and (b) 1.1×10^8.

Figure 4 shows the lifetime of the quadrupole magnetic trap. The number of atoms initially loaded into the quadrupole magnetic trap is 4×10^8. The change of the number of atoms in the magnetic trap with time is shown by the squares dots in Fig. 4. When the mechanical switch is on, the quadrupole trap lifetime is longer than 10 s, which meets the requirements of the evaporative cooling experiment.

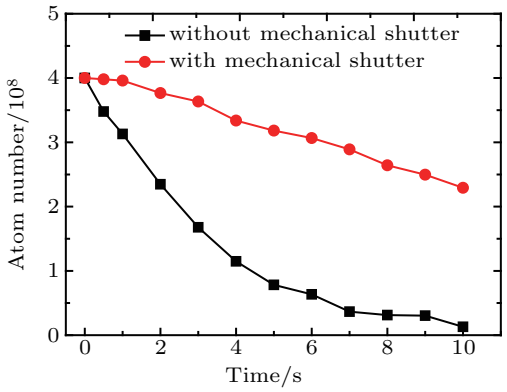


Fig. 4. Lifetime measurement of ^{87}Rb atoms in the quadrupole magnetic trap.

Immediately after PGC, the current in the trapping coils is switched on to capture the atoms in a quadrupole trap, and then ramped to full current over 50 ms, generating the maximum gradient of ∼150 G·cm^{-1}. As the center of the quadrupole magnetic trap $B = 0$, Majorana transition will occur and the atoms escape from the trap, making it impossible to reach the phase transition point of the BEC using the quadrupole magnetic trap alone. In order to avoid the loss of atomic number due to the Majorana transition, simultaneously with the magnetic field ramp up, the power from two separate laser beams, intersecting at 30°, is increased to produce a hybrid

quadrupole-magnetic and optical-dipole trap for the atoms. During 2 s, the magnetic and optical parameters of the hybrid trap are kept constant, while the clouds are cooled by rf evaporation of ^{87}Rb atoms in the $|F=1, m_F=-1\rangle$ ground state. To perform evaporative cooling in the magnetic trap, an arbitrary waveform generator (Agilent 33250A), a voltage-controlled attenuator and a 4 W rf amplifier (MiniCircuits TIA-1000-1R8) are used to drive a two-loop coil of radius 12 mm placed against the glass cell. The function generator produces a logarithmic rf sweep from 10 MHz to 4 MHz over 2 s. The magnetic field is then ramped to zero over 0.5 s, loading the atoms into the pure crossed dipole trap, whilst forced rf evaporation continues until the magnetic field is off. At this stage we have a sample of 2×10^7 ^{87}Rb atoms at temperatures close to 2 μK. The schematic of our BEC experimental sequence is shown in Fig. 5.

In the optical dipole trap, over 3 s, the depth potential is smoothly ramped down to its final value for an escape evaporation cooling process. The final power of two dipole beams are reduced to 0 W and 1.9 W, respectively.

Following pre-cooling in the QUIC trap, we are able to produce pure ^{87}Rb $|F=1, m_F=-1\rangle$ condensates containing up to 2×10^6 atoms after 3 s of evaporation in the optical dipole trap. Figure 6 shows the formation of an ^{87}Rb condensate with the decreasing power in the dipole beams. The elongation of the cloud along the tight trapping direction demonstrates the reversal of aspect ratio characteristic of BECs. The presence of a BEC is clearly indicated by the emergence of a bimodal momentum distribution and by the mean-field driven expansion which causes the cloud to expand more rapidly along the direction of tightest confinement.

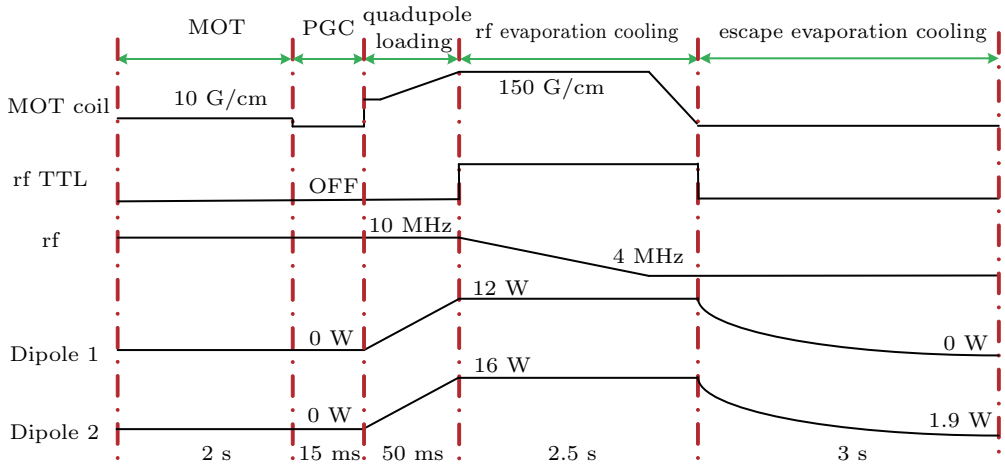


Fig. 5. Schematic of the experimental sequence.

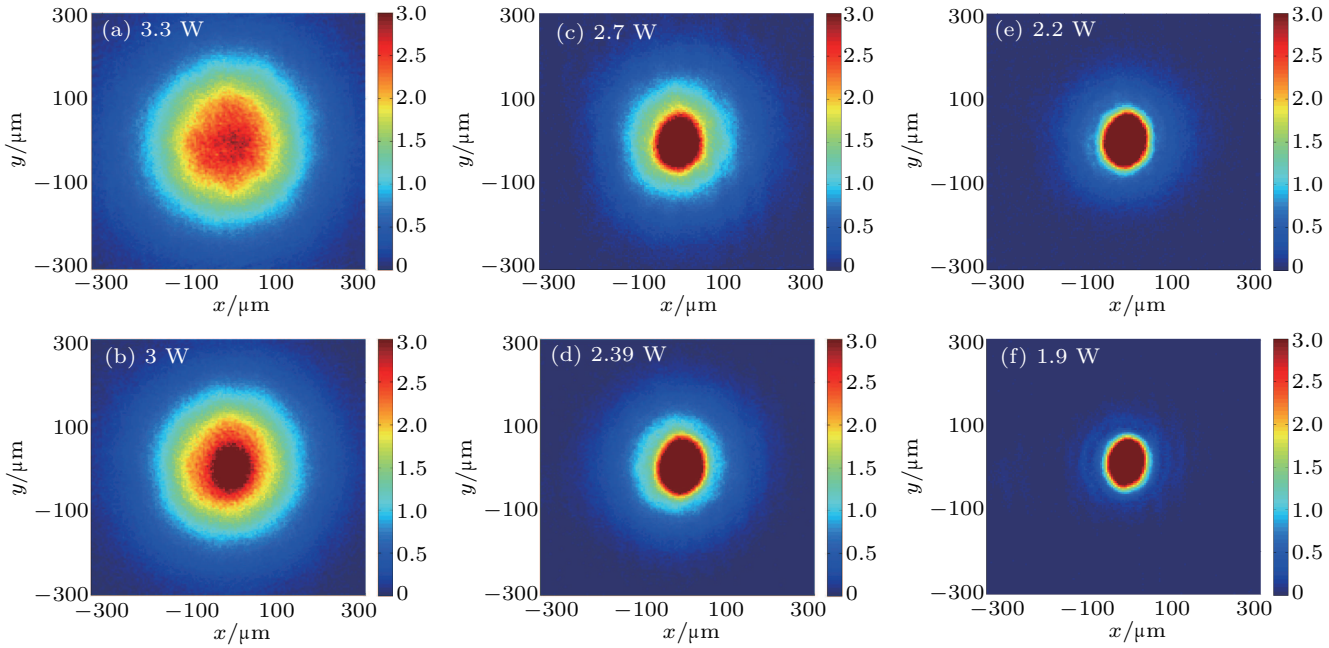


Fig. 6. Absorption images taken after 20 ms of ballistic expansion showing the formation of an ^{87}Rb BEC as the depth of the crossed dipole trap is reduced.

When the cut-off power of dipole laser 1 is 3.5 W, the maximum optical depth (OD) of the atom cloud is 3, the atoms number is around 9×10^6, and the temperature of the cloud is 382 nK. At this time, no condensed state has appeared. Gradually reduce the cut-off power of dipole laser 1, the phase transition point of the BEC is observed at 3.3 W, and the corresponding temperature is 330 nK, but there are many surrounding hot atoms at this time. Continue to reduce the cutoff power of dipole light 1, as shown in Figs. 6(c)–6(e), the optical thickness of the atomic group gradually increases, and the maximum OD at the center of the cloud is gradually saturated. At this time, the BEC atomic group gradually becomes smaller, and the surrounding hot atoms gradually reduce, which shows that during the entire evaporative cooling process, the elastic collision rate between the remaining atoms in the potential well is continuously increasing, and the evaporation process continues to be efficient. Finally (Fig. 6(f)), when the cut-off power of dipole laser 1 is 1.9 W, a pure BEC is prepared, the temperature is around 50 nK.

Figure 7 shows the formation of condensate as the power in the dipole beams is reduced. The fits showing the transition from a thermal Gaussian distribution, to a bimodal distribution, to a nearly pure condensate.

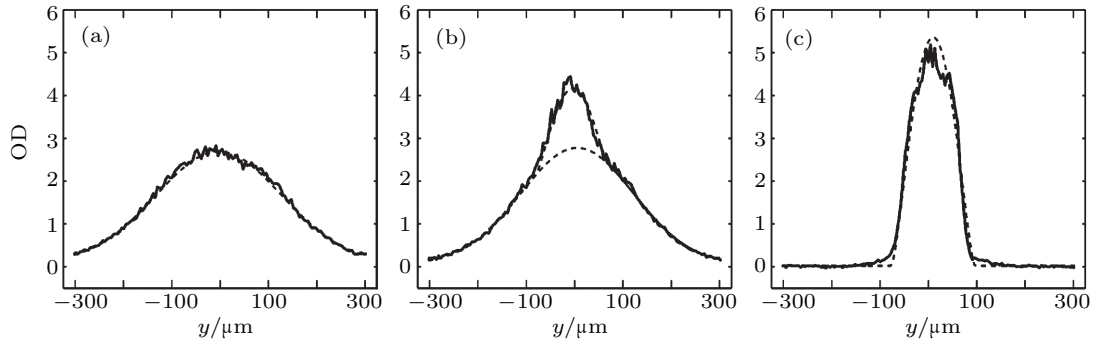


Fig. 7. Optical depth profiles along the y direction: (a) thermal Gaussian distribution, (b) bimodal distribution, (c) nearly pure condensate.

4. Conclusion

A simple and robust apparatus to produce ^{87}Rb BECs has been demonstrated. A compact low-noise digital OPLL board is used for phase locking between two ECDLs, our optical design, on the one hand, saves space and makes the optical path simpler. On the other hand, only an SP AOM is used, so that more power of the laser beam reaching the glass cell can be maintained, improving the experimental efficiency. We obtain a nearly pure BEC of 2×10^6 ^{87}Rb atoms every 7.5 s. The ability to achieve high duty cycle and large BEC number opens the perspective to use BECs in high precision measurement applications such as atomic clocks or accelerometers.

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