Miniaturized optical system for atomic fountain clock

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Using modularized components, we have built a miniaturized optical system for ^{87}Rb atomic fountain clock that is fitted on an 80 cm × 60 cm optical breadboard. Compared with the conventional optical setup on the table, our system is more compact, more robust and miniaturized. Taking advantage of this system, laser beams are transmitted through eight optical fibre patch cords from the optical breadboard to an ultra high vacuum system. This optical setup has operated for five months in our fountain system and required no alignment.

Keywords: atomic clock, laser cooling

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1. Introduction

Fountain clock with laser cooled atoms is playing an important role in the field of metrology,[1,2] time keeping,[3,4] navigation system,[5] and other areas of accurate measurement.[6,7] Typically, a fountain clock consists of an ultrahigh vacuum (UHV) chamber, optical system and a microwave source.[8−12] The operation of a fountain clock involves the following steps. First, a cloud of cold atoms is trapped by magneto–optical trap (MOT)[13] or optical molasses (OM)[14−16] formed by three pairs of counter-propagating laser beams. Secondly, the cloud of atoms is launched by the so-called moving molasses which has a frequency difference between the downward and the upward laser beams. Thirdly, the cloud of atoms interacts with microwave twice on its way up and down passing through a microwave cavity during its ballistic flight. Fourthly, the atomic ground state hyperfine structure population distribution is detected by laser-induced fluorescence. The optical system provides the laser sources for trapping, cooling, launching and detecting the cold atoms in the UHV chamber. It is now a standard method to inject the six cooling laser beams and the three detection laser beams into the UHV chamber through optical fibres for robustness.[9,10,17]

Dozens of optical elements will be used in such a fountain optical system. According to the manipulating mode of the laser beam, we need the polarizing beam splitters (PBS) to polarize the laser, the wave plates to rotate the laser polarization plane, the mirrors to reflect the laser beam and the acousto–optic modulators (AOM) to shift the frequency of laser. A conventional optical system is used to fit these optical components on a specific mount which is fixed on a post. Dozens of post will be held on an optical table as large as 1.2 m × 2 m separately.[12,18] This can clearly restrict the versatility of an atomic fountain where space and weight may be limited or where mobility is required.[19,20] Such an optical setup is also sensitive to temperature change and mechanical creep because of the long optical path lengths, resulting in the need for frequent realignment.

In this work, we develop a miniaturized optical system by using modularized components. This setup has operated for five months in our fountain clock system and required no realignment.

2. Optical system architecture

The schemetic of the optical system is shown in Fig. 1. The master laser is an external cavity diode laser (ECDL).[21,22] After passing through a 35-dB optical isolator, the laser beam is split into three beams. One beam is used for frequency locking to the saturation absorption crossover resonance of rubidium ($F = 2 \rightarrow F' = 3, F = 2 \rightarrow F' = 2$). At this point, the laser frequency is red detuned (133 MHz) to the resonance frequency of rubidium $F = 2 \rightarrow F' = 3$. The second part of the beam makes a double-pass through

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an acousto–optic modulator (AOM7) before coupling into two optical fibres. It is used for atomic detection and selection and the laser power is adjusted and controlled by the AOM7 radio frequency (RF) power. The AOM7 operates at a frequency of 68 MHz. The third beam makes a double-pass through AOM1 and is divided into two parts. One part goes through AOM2 and is then locked to slave laser 1 and the other part goes through AOM3 and is locked to slave laser 2. After passing through an optical isolator, the slave laser 1 beam passes through a 74-MHz AOM4 and is divided into three beams. The slave laser 2 beam is treated in a similar way to that for slave laser 1. The two slave lasers then provide six beams (3+3 counter propagating) to make the optical molasses geometry. The AOM1 RF frequency can be tuned from 133 MHz to 95 MHz corresponding to the cold atom trapping phase and the cold atom polarization gradient cooling phase during the fountain clock operation. In the trapping phase, AOM2 and AOM3 operate at the same frequency (75 MHz). By tuning the frequencies of AOM2 and AOM3 in opposite directions, the trapped cold atoms can be launched with moving molasses method. AOM4 and AOM5 operate at the same fixed frequency (75 MHz). The RF powers of AOM4 and AOM5 determine the six capturing and cooling light intensities. The second ECDL is frequency locked to the crossover resonance of rubidium ($F = 1 \rightarrow F' = 1, F = 1 \rightarrow F' = 2$). The beam passes through a 78-MHz acousto–optic modulator (AOM6) and is split into two parts. One part of the beam is merged into trapping light beam used as re-pumping light and the other part is coupled into a fibre and used as re-pumping light in detection system.

The schematic diagram of optical system is shown in Fig. 2. Different from that in the conventional optical system where every component is fixed on the optical table separately, in our system a group of optical components are integrated into a module to realize some special function in the optical system. According to the functions to be realized, there are needed a laser beam transform module,

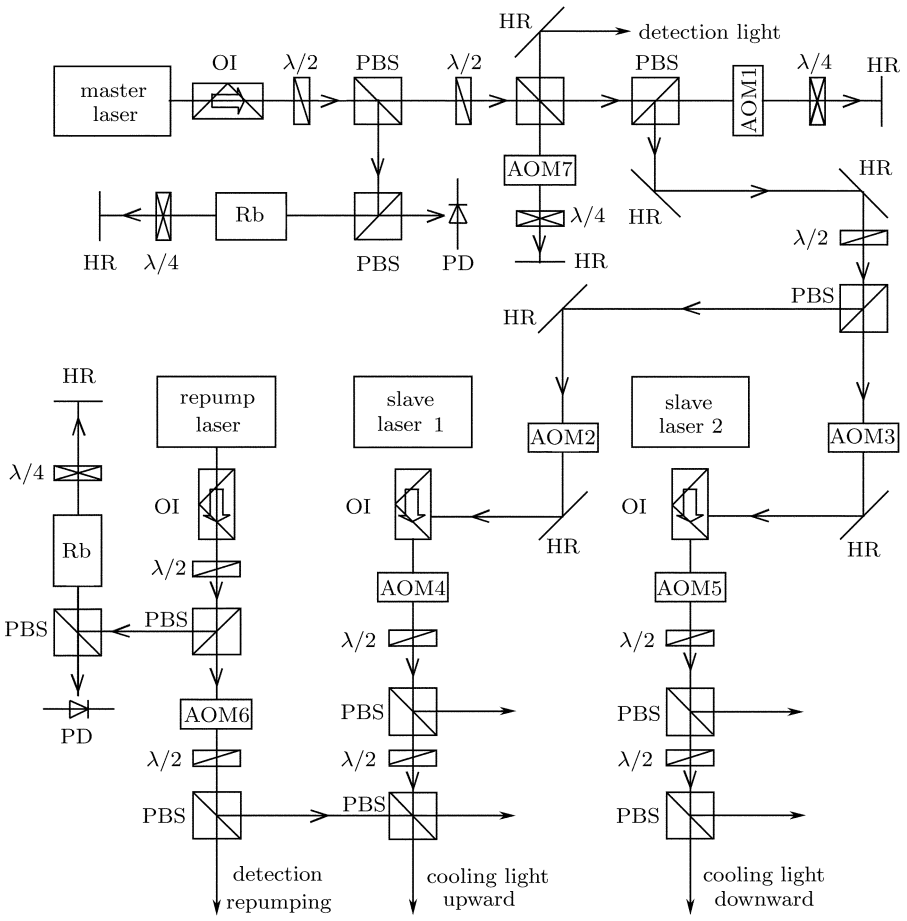


Fig. 1. Optical system schematic diagram, OI: optical isolator, $\lambda/2$: half-wave plate, $\lambda/4$: quarter-wave plate, AOM: acousto–optic modulator, PBS: polarization beam splitter, HR: highly reflective mirror, Rb: rubidium absorption cell, PD: photodiode.

a laser beam split module, a laser to fibre coupling module, an AOM double pass module and so on. In every module, a group of elementary optical components such as mirror, wave plate and lens are fixed on a small base plate. Integration of these modules by bolting them on an 80 cm × 60 cm × 1.8 cm aluminum optical breadboard builds up the entire optical system. Before the integration process, each module is optically pre-aligned. The heights of all laser beams above the optical breadboard in different modules are designed to be the same, which is conducive to the integration process.

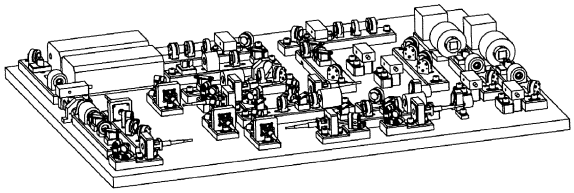


Fig. 2. Optical system.

Figure 3 is a module of an AOM with a double pass. On the base plate, from left to right there are a 0-degree mirror, $\lambda/4$ wave plate, lens, an AOM and a 45-degree mirror. The distance between the lens and the 0-degree mirror is one focal length, thus forming a "cat eye" arrangement. A linearly polarized laser beam from other modules will be introduced to the 45-degree mirror. After the AOM, the 1-order diffraction beam of the input beam will be reflected by the 0-degree mirror on the way of its input path and its polarization plane will be rotated 90-degree by the $\lambda/4$ wave plate. After double passing through the AOM, the 1-order diffraction light of the output beam will transmit in its input way. During the adjusting, the actual laser beam height above the breadboard will have ±0.5 mm deviation from the design height. But this is good enough to achieve about 85% diffraction efficiency on the first pass through the AOM by adjusting the AOM on one-dimensional (1D) translation and 1D rotation in the plane parallel to the breadboard.

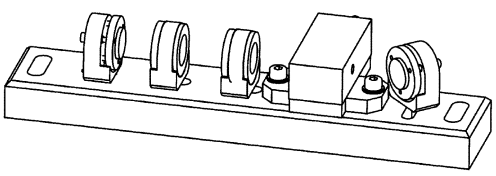


Fig. 3. AOM double pass module.

3. Performance and conclusion

As shown in Fig. 1, the six cooling laser beams and the two detection laser beams are guided to the fountain vacuum system by eight polarization maintaining fibres. The output laser beam of each fibre used for trapping and cooling is collimated to a beam waist radius of 10 mm at $1/e^2$. The maximum intensity of about 7 mW/cm^2 is obtained in the centre of each beam excluding about 1-mW re-pumping laser light in two of the six fibres. The output beam of the detection laser is collimated and divided into two beams with the same size, 7 mm × 13 mm. The intensities of the two detection laser beam are both 0.2 mW/cm^2. The re-pumping beam for detection has 20-μW laser power and the laser beam is collimated to 7 mm × 13 mm which will be used to pump the rubidium atoms from ground hyperfine state $F = 1$ to state $F = 2$.

Although there is no optical intensity stabilization servo system used, the optical system is proven to maintain a stable alignment over a long period of time. By monitoring the output powers of six cooling fibres, we find that the power variance has been less than ±5% for five months without adjustment. This is a significant improvement on our conventional optical system that requires adjustments in several days. Taking advantage of this optical system, we can trap about 10^5 to 10^7 rubidium atoms in each fountain cycle by varying the trapping time and the trapping laser intensity in optical molasses. In the long term fountain operation, the atom number variance is about 15%. Figure 4 shows the detected atom number variance in about 50000 serial fountain cycles. In these test data, part of the atom number variance is contributed by the variance of detect laser intensity. This variance can be canceled by using a laser intensity stabilization system.

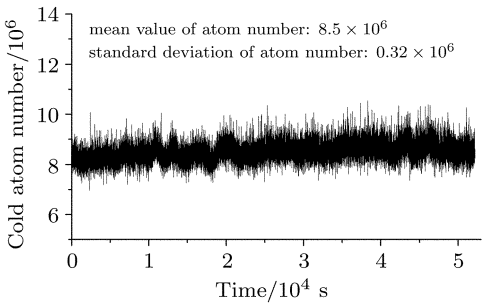


Fig. 4. Detected atom number variance in about 50000 serial fountain cycles.

Using the time-of-flight (TOF) method, we measure the temperature of cold atomic cloud. Figure 5 shows the 1D distribution when the atomic cloud fly over the detection laser beam twice. We infer that the 1D temperature of the atomic cloud is 2.5 μK based on the thermal expansion speed of the cold atom cloud.[23]

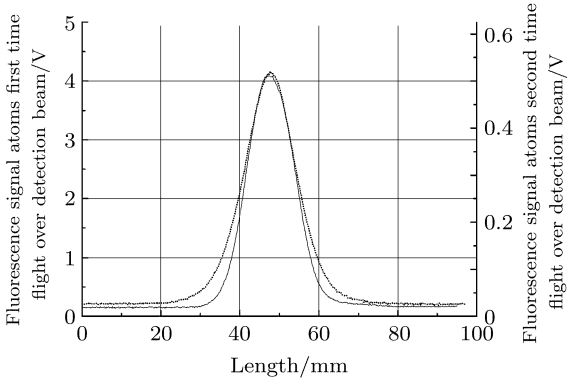


Fig. 5. One-dimensional spatial distribution of launched cold atomic cloud. The data are acquired by monitoring the temporal change in fluorescence intensity with atoms flying over the detection laser beam. The horizontal axis is rescaled from detection time to position using the atomic flight velocity. Solid line denotes the first time atoms flight over detection beam, $\sigma = 5.7$ mm. Dashed line represents the second time atoms flight over detection beam, $\sigma = 6.6$ mm. The 1D temperature of the atomic cloud is 2.5 μK.

In conclusion, we have constructed a miniaturized optical table that is more compact and more robust than the conventional optical setup. The colder atoms can reach temperatures ranging from 4 μK to 2.5 μK compared with previous experimental results acquired by using our conventional optical setup.[12] This means that the cold atom cloud expands more slowly, so the atom number loss rate due to thermal expansion will be reduced. At the same time, the slower diffusion speed of atoms will reduce the cavity phase shift due to transverse microwave field phase variation in the cavity.[24] On the other hand, the continuous operation time of the system is much longer (dozens of hours to several weeks) than our conventional optical system. The main reason to break the system continuous operation is that our fountain is an experimental system up to now. We have to test its characteristics such as sample atom number and temperature first other than operating it as a clock. During the operation break, no optical realignment is required. This demonstrates that the miniaturized optical system is useful for long-term atomic fountain operation and convenient in transportation. We can say that this optical system paves the way for reducing the clock uncertainties and also for evaluating the clock instability because in these respects a long-term operation fountain is required. This optical table design is also well conducive to applying the system to many experiments in which laser cooling and trapping techniques are needed.

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