Fold optics path: an improvement for an atomic fountain*

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A fold optical path is utilized to capture and launch atoms in the atomic fountain. This improved technique reduces the laser power needed by 60 percent, facilitates suppression of the laser power fluctuations, and leads to a more simple and stable system.

Keywords: fold optics path, atomic fountain, laser power

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1. Introduction

Atomic fountains (AFs) have broad applications in precision measurement fields. The uncertainty of the fountain clock has reached the 10^{-16} level,[1] while gravimeters and gravity gradiometers can measure the gravity and its grade at 10^{-9}.[2] PHARAO (Projet d'Horloge Atomique à Refroidissement d'Atomes en Orbite), a cold space clock based on the fountain clock technique, will be set up in an international space station in 2013.[3,4] Its uncertainty is expected to be about 1×10^{-16}. A similar plan is being executed in China.

Since the first fountain for metrological use was developed at Observatoire de Paris/France,[5] the design of AFs has become the standard for almost all subsequently constructed fountain clocks. The setup includes magnetic–optical trap (MOT)/optical molasses (OM) trap cold atoms, OM keep cooling, and optical moving molasses (OMM) launching atoms. Most AFs have the so-called (1,1,1) laser beam configuration, shown on the left side of Fig. 1, which consists of three orthogonal pairs of counter-propagating laser beams; three laser beam pairs are likewise arranged symmetrically around the vertical axis at an angle of 54.7° to the vertical. The six laser beams (SLBs) are divided into two groups: pointing upwards and downwards, respectively. At the MOT and OM stages, the SLBs keeps the same frequency ν; while at the OMM stage, the upward ones turn to $\nu+\Delta\nu$, and the downward ones change to $\nu-\Delta\nu$ to control the velocity of the atoms. Thus the atoms are launched along the vertical direction at a velocity of $\sqrt{3}\lambda\Delta\nu$, where λ is the wavelength of the laser.

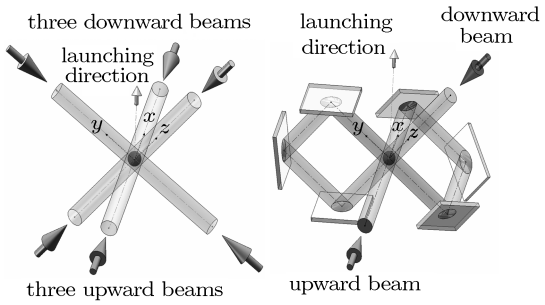


Fig. 1. The (1,1,1) fountain launching structures of a SLB system (left) and a FOP system (right).

AFs provide exciting results in their applications. However, they are strict at the environment and very difficult to run continuously due to the complex optical system, so, until now, there is no commercial AF working either as a clock or as a gravimeter, and this is the most important factor restricting its application in a space clock. Thus we substitute the SLBs with a fold optical path (FOP) scheme to achieve a more simple and stable system.

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2. Initial optical setup with SLB in our atomic fountain

AFs of different research groups all have the SLB scheme as shown in Fig. 1 (left), with similar optical paths. The optical system of our AF initially has the standard SLB design, as shown in Fig. 2. A 1-W laser (TA100, TOPTICA Comp.) acts as a master laser with an output of 600-mW power for six capturing-launching (CL) beams, state-selecting (SS) beam, and detecting beam, while a 50-mW laser (DL100, TOPTICA Comp.) is used to supply repumping beams for the CL and the detecting stage. The frequencies of both lasers are locked at a saturated absorption peak of the D2 line of ^{87}Rb isotope. Four acousto–optical modulators (AOMs) are used to shift precisely the frequencies of light through a double-pass optical path. The lasers then split and transfer through fibres to a vacuum chamber. The power of each CL laser beam is about 25 mW with a diameter of 20 mm. The total power of the SS beam and the detecting beam is about 10 mW, and several microwatts are enough for the sum of the repumping beams of the fountain. So, the total power of the master laser should be greater than 250 mW.

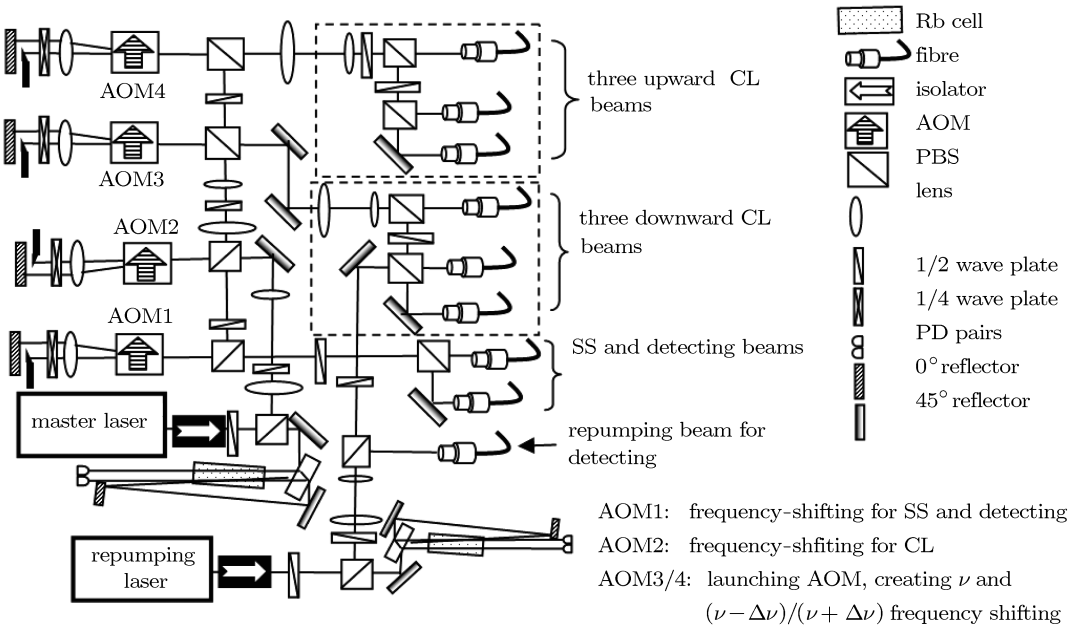


Fig. 2. Optical path of the atomic fountain at Shanghai Institute of Optics and Fine Mechanics (SIOM).

MOT and OM require that the intensities of all counter-propagating laser beams are well balanced; the error should be less than 10%. The balance is difficult to maintain because much noise, mainly corresponding to fibres, makes the power of the output laser fluctuate. This is one of the principal elements affecting the continuous and reliable running of AFs, and is fatal for a cold atomic clock working in space because self-action, continuous running, reliability, and stability are the basic requirements. In addition to many passive actions to reduce the variations, active controllers have been used to provide feedback on the laser power's fluctuation. For example, at PHARAO, many piezoelctric ceramic (PZT) transducers were used to mount fibre coupling mirrors to control the output power by modulating the coupling efficiency.[4] And for fountains of the United States Naval Observatory (USNO), polarization-beam-splitters (PBS) are substituted with polarization-maintaining fibre splitters to reduce the fluctuations of laser power. Even so, a laser power stabilizing system is required for every set of fibre splitter system.[5]

3. Improving the optical setup with a fold optical path scheme

We simplify the optics system of the fountain by using FOP to set up the CL zone, as shown on the

right side of Fig. 1. Reflected by six pieces of 45° high-reflecting (HR) mirrors, a laser beam input along the $+x$ direction passes the centre three times successively along the $+x$ direction, then the $+y$ direction and the $+z$ direction. Another counter-propagating laser beam is applied along the $-z$ direction; thus three orthogonal pairs of counter-propagating laser beams set up the CL zone. Adding a pair of anti-Helmholtz coils along the y direction, the polarization of the three pairs of laser beams would fit the requirement of MOT once the two input beams have the right circular polarizations. It becomes a σ^+–σ^- OM when the coils are removed, and it changes to a normal lin⊥lin OM when the beam input along the $+x/-z$ direction is linearly polarized in the z/x direction, or when both are linearly polarized in the y direction. Obviously, when the two beams change the frequencies, respectively, to $\nu + \Delta\nu$ and $\nu - \Delta\nu$, they make a normal OMM. Thus, the structure fits the polarization requirements of MOT and σ^+–σ^-/lin⊥lin OM; and the FOP system can substitute the normal SLB, with the six mirrors used instead of the four laser beams. The FOP structure, which has formerly been used in MOT and optical lattices,[6] fits all requirements at every stage of AF, including trapping, sub-Doppler cooling, launching, and OMM-cooling.

The FOP has great advantages over the SLB. First, the requirement for laser power decreases to a little more than 30% of the SLB system, viz, less than 100 mW. While the output of many diode lasers are more than 120 mW, this means that a single diode laser can work as a master laser without any amplifiers, which leads to a more simple and reliable system. Second, the FOP structure reduces the number of fibres, their accessories such as input coupler and output collimator, and other optical units, such as wave-plates and PBSs; thus, the optical system is greatly simplified, which also means a more stable system. Third, it is easier to control the fluctuations of the CL beams, because we now only need to adjust the diffracting efficiency of two launching-AOMs (AOM3 and AOM4 in Fig. 2).

However, FOP has to overcome two difficulties: one is precise control of the beam angle. For a 1-m launching-height AF, the anglular error of every beam should be less than 1 mrad; the alignment is difficult because a beam in the FOP scheme experiences six mirror reflections. We first adjust one beam (such as the upward beam) at one orientation (such as $+x$ orientation), then add one set of three-mirror system and adjust another orientation ($+y$ orientation), then add another set of three-mirror system and adjust the other orientation ($+z$ orientation). With the help of auxiliary laser beams and auxiliary devices, such as a collimator and a diaphragm, we make sure that the accuracy of every step of adjustment is limited to less than 1 mrad. We then add another beam (downward beam), adjust inputting mounts to make two counter-propagating beams coincide (with angle/position error less than 0.1 mrad/0.5 mm respectively). Then we carry out atomic fountain experiments to optimize the FOP system by some fine adjustments, and lock every adjustable mount. The structure is probably not the best working model but it is very stable; and for a device, the stability is more important than the best working data.

The other difficulty of realizing FOP is power balance of the counter-propagating beams. The FOP beam power is reduced by reflecting/transferring loss (RTL) of mirrors/windows, and optical scattering loss (OSL) of cold atom cloud; thus it is impossible to have the same power balance at three orthogonal directions. The RTL can be limited to an acceptable level by a fine film coating, for instance, if the loss of every window/mirror is less than 0.1%, which is attainable, the total unbalance due to RTL will be less than 1%. And in fact, as shown in the following, an RTL even as large as 5% is still acceptable for AF. The OSL is a complicated process, which affects the efficiencies of trapping, cooling, launching, and recooling. For AFs where the density of cold atoms is as low as $(10^9$–$10^{10})/\mathrm{cm}^3$, the optical thickness is at the level of 0.01. Thus the OSL is limited, so the authors in Ref. [6] have not discussed it. The OSL is a fixed system error that reduces the number of signal atoms but causes no heating to the cold atoms, unlike the laser power fluctuations of SLBs. So although FOP cannot provide accurate power balance, it can work as well as a SLB, and no additional component is required to compensate for its leakage.

4. Testing the FOP in an atomic fountain clock

We tested the FOP in an atomic fountain clock. The device, as shown in Fig. 3, consists of a CL chamber, an SS cavity, a detecting chamber, and an interacting chamber. A TE011 cylindrical microwave cavity with resonance frequency of 6.834 GHz and

a quality factor of 18000 is set at the bottom of the interacting chamber. Two ion pumps set at the bottom and the top maintain a vacuum degree of 1×10^{-7} Pa. A rubidium cell connected with the CL chamber supplies the background gas of rubidium. The AF uses a low-density atom cloud for lower collision-frequency shift, so a low magnetic gradient (about 1.5 Gs·cm^{-1}/0.8 Gs·cm^{-1} (1 Gs=10^{-4} T) at axial/radial direction of coil pair) MOT is set.

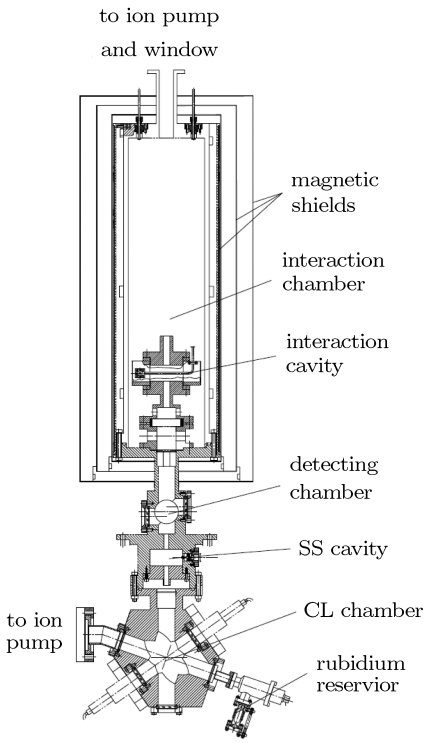


Fig. 3. The scheme of rubidium AF at SIOM.

We first use a SLB scheme. About 1×10^8 ^{87}Rb atoms are trapped by MOT (500-ms loading time), cooled and launched by OM and OMM, tossed to its apogee and fall down, and detected by photodiodes. When the clock works, atoms go through state-selecting and microwave-interacting stages in their projectile motion. As given by the TOF signal, the atoms' temperature was 4 μK, and the falling atom number was 4×10^6 populated on five magnetic sublevels of $F=2$, $5^2S_{1/2}$, of which 8×10^5 were state-selected. The AF experiments of ^{85}Rb were also taken on the device; the temperature and the number of falling atoms were 2.5 μK and 1×10^7, respectively.

We then replace four sets of fibre systems with two mirrors systems, each of which is composed of three 45° HR mirrors. Two of the mirrors are fixed on two-dimensional mounts and the other is fixed on a mount. All three mounts are set on an L-shape aluminum plate, with the plate fixed to the vacuum chamber. By adjusting the mounts, the errors of the laser beams' angles are limited to about 1 mrad, which are similar to the errors of earlier six-fibre systems. The reflection loss of the 45° mirrors system was measured as less than 1% for the light of s-polarization and about 2% for p-polarization. The transferring loss of windows was also measured, with every pair of windows at the three orthogonal directions, approximately 1%. Thus, assuming an ideal condition for power balance that the counter-propagating beams have equal power at the y direction, there is still an error of about 5% in the x and z directions. This limit can be improved by using better coating films for the mirrors and windows.

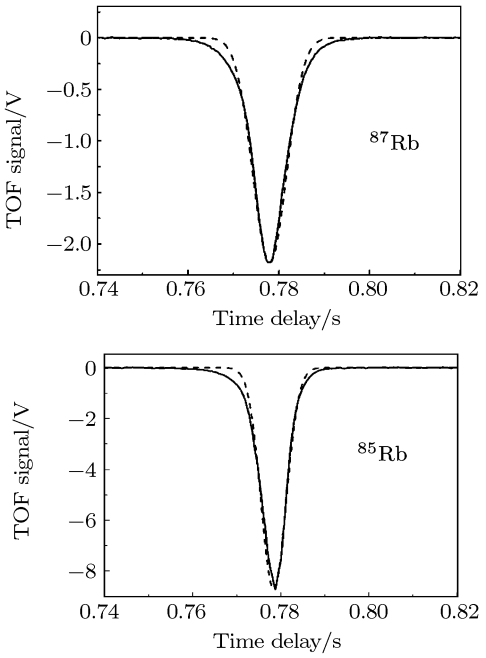


Fig. 4. TOF signals (solid line) and their Gauss fitting (dash line) of ^{87}Rb atoms (top) and ^{85}Rb atoms (bottom).

Besides the changes mentioned above, every detail of the experiments is the same as that of the SLB system, that is, the same c-field, same maximum power with same diameter of laser beam, same time sequence, same launching height, and same detecting. The TOF signals of the two isotopes are shown in Fig. 4. The cold atoms were cooled down to a temperature of approximately 2.3 μK and 1.6 μK for ^{87}Rb and ^{85}Rb, respectively, and the number of falling atoms was 7×10^6 and 1.5×10^7. This means that more falling atoms are obtained with lower temperatures

for both isotopes in the improved device. These results are remarkably better than those of the SLB but slightly poorer in comparison with the best results of the no-Raman-side-cooling fountain.[1)] We think that the improvement in the results is due to suppression of the power fluctuations of the laser beams by reducing the number of CL fibres from 6 to 2.

5. Conclusion

The FOP has worked continuously at our fountain for about one and a half years, with no adjustments to the optical path during this period. The FOP scheme provides better results than SLB in our experiments. This scheme is not perfect because the CL beams cannot be exactly balanced at three directions due to various kinds of losses. However, it fits every requirement of fountains and is simpler. It reduces the laser power by two-thirds and greatly simplifies the optical path, thus making the optical system more stable and reliable. It is especially significant for cold space clocks because fewer units (especially laser source), less power supply, less control, and high stability are the prime design considerations for devices in space.

Acknowledgment

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[1)] The temperature of the ^{85}Rb fountain is not indicated in the references. Because the temperature of OM cooling is related to the magnetic moment of atoms' cooling state, $F = 2$ for ^{87}Rb, $F = 3$ for ^{85}Rb, and $F = 4$ for ^{133}Cs, we can infer that the temperature of ^{85}Rb should be higher than that of ^{133}Cs (0.7 μK according to the reference "Salomon Ch, Dalibard J, Phillips W D, Clairon A and Guellati S 1990 *Europhys. Lett.* **12** 683) and lower than that of ^{87}Rb.