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REVIEW ARTICLE

The transportable cesium fountain clock NIM5: its construction and performance

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The second laser cooling cesium fountain clock NIM5 at the National Institute of Metrology (NIM) China adopts the (1,1,1) direct optical molasses (OM) configuration. NIM5 has been running with a stability of 3×10^{-15}/d and an operation ratio of 99% since 2007. Preliminary evaluations of NIM5 in 2008 showed a typical combined uncertainty of 3×10^{-15}. The NIM5 clock is operating in parallel with NIM's first fountain clock NIM4. NIM4 and NIM5 are used to steer the frequency of the calculated NIM atomic time TA-c(NIM) and the first set of results are promising. We are now at the stage of comparing the frequency of NIM5 with UTC to support the independent frequency shift evaluations of NIM5 and contribute to the international atomic time in the near future.

Keywords metrology, time and frequency standard, fountain clock

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Contents

1 Introduction

The first laser cooling cesium (Cs) fountain frequency standard NIM4 at the National Institute of Metrology (NIM) China has been running since 2005 with an operation ratio (life time) of 98% (provides 98-day valid data in 100 days) and a typical evaluation uncertainty of 5×10^{-15} [1, 2].

From 2004, we started to build the second Cs fountain clock NIM5 based on experiences learned from the NIM4 and references to the latest developments of fountain clocks worldwide.

NIM5 is designed and constructed to work accurately, reliably, and subcontinuously and to be transportable. It can operate in either magneto optical trap (MOT) or direct optical molasses (OM) mode to prepare the cold atoms. Unless otherwise specified, the experiments presented in this paper were performed in direct OM.

The paper describes the design, construction, and performance of NIM5, especially those different from NIM4. This is because the design of NIM4 follows essentially the CsF1 clock of BNM–SYRTE France, and the latter was presented in many papers, such as Refs. [3, 4].

2 Design and construction of NIM5

The overall assembly of NIM5 consists of a 0.6 m× 0.8 m×1.8 m physical package, the laser optics system on a 1.2 m×0.9 m bench and electromicrowave system in two racks of 0.6 m×0.6 m×1.8 m.

2.1 The physical package

Figure 1 shows the schematic drawing of the physical package of NIM5 clock.

An oxygen-free copper (OFC) fountain tube and an OFC cylindrical TE011 Ramsey microwave cavity with $Q = 18\ 000$ in the tube are surrounded with a four-layer

μ-metal magnetic shield system. Another OFC selective cavity (also TE011) is inserted into the top part of the MOT body just underneath the detection zone. The oscillation frequency of the Ramsey cavity was adjusted by controlling its temperature to around 50°C. Three thermometers are put on the outer surface of the fountain tube to measure the temperature with uncertainty of 0.4 K for the correction of black body radiation frequency shift.

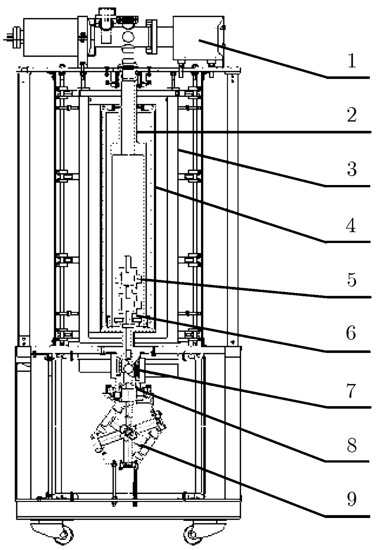

Fig. 1 Schematic drawing of NIM5 physical package. 1: Top ion pump (bottom pomp not showed); 2: Fountain tube; 3: Magnetic shield; 4: C-field coil; 5: Ramsey cavity; 6: Upper selection cavity; 7: Detection part; 8: Bottom selection cavity; 9: MOT/OM.

The detection assembly is located between the fountain tube on top and the MOT/OM body below.

The MOT/OM body was machined from an aluminum alloy block. The angles of surfaces, on which the MOT/OM beam collimators (described later) are fixed, on the MOT/OM body were measured and corrected by means of manually polishing.

In NIM4, two ion pumps are connected to the MOT chamber. That leaves a dead space at the top part of the fountain tube, this situation is not preferred for good vacuum. Whereas in NIM5, one pump is connected to the MOT/OM and another one to the top of the fountain tube to realize a better vacuum (better than 7×10^{-8} Pa) there so as to reduce the collision of the cold Cs atoms with background gases because the atoms spend more time in their ballistic movement on the upper part of the fountain tube.

2.2 The laser and optics system

An external cavity diode laser (ECDL) is frequency shifted and locked to the $F = 4$ to $F' = 4$ and $F' = 5$ crossover transition of the Cs D2 line as the master laser [5]. One F–P slave diode laser working with 140 mW output, one single-pass AOM, and one 1×3 single mode (SM) polarization maintenance (PM) fiber coupler constitute either channel of the up or down (1,1,1) MOT/OM optics. More than 11 mW optical power is available from each of the six outlets of the two 1×3 couplers. Each light is collimated to a beam with diameter of 26 mm as one of the six MOT/OM beams by an individual collimator assembly.

The fiber couplers were custom made. Their polarization extinction ratio was tested to be better than 1000 and the change of their optical splitting ratio with time less than 0.2% over 3 months. The fiber couplers are compact and robust and meet the requirements of the design.

The atom clouds are launched in an upward moving-wave OM, which is realized by reverse frequency detuning of the three downward and another three upward OM lights. When a single-pass AOM performs the detuning, it introduces an angle deviation on the outlet light. Fortunately, the angle deviation does not change the optical spot position on the fiber inlet face through the collimating-focusing optics (Fig. 2). Experiment showed that the practical fiber coupling efficiency of the light into the fiber changes is less than 2% before and after detuning with the single-pass AOM optics.

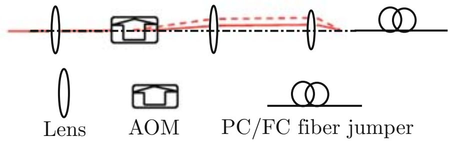

Fig. 2 The AOM collimating and the fiber couple-focusing optics.

A 5-mW light from the master laser is collimated and cleaved into two beams with rectangle section of 2×20 mm^2 as the detections.

The detection beam in horizontal is also used to push the $|F{=}4,\ m \neq 0\rangle$ atoms away while leaving the upgoing $|F{=}3,\ m{=}0\rangle$ atoms unaffected after the selection of the atom states is performed just underneath the detection zone.

2.3 The electro-microwave system

Two dedicated Cs frequency synthesizers, synchronized to the master H-maser of the NIM timekeeping clock assembly, generates the microwave for atom state selection and for atom interrogation. The homemade interrogation synthesizer, based on the scheme of reference [6], produces an extra stability in phase, super pure in spectrum, and highly tunable in extremely fine step probing microwave. To eliminate the microwave power-related frequency shifts, it is preferable to switch off the microwave before the atom cloud enters and after it leaves the Ramsey cavity ($\pi/2$ microwave field) in a fountain circle. In another hand, the atoms in their up and down movement interact with two $\pi/2$ microwave fields in a Ramsey circle. To escape from the frequency shift induced by microwave phase difference, these two $\pi/2$ microwave have to be strictly phase continuous. An interference microwave switch [7] has been built on the output port of the interrogation synthesizer to produce the pulsed resonance microwave for the Ramsey interactions, with the phase of the pulsed microwave remaining undisturbed. Another method based on the similar idea but realized through direct detuning, the output frequency of the direct digital synthesizer (DDS) in the interrogation synthesizer is also under consideration. The key technique for the DDS method is also to realize the frequency flip–flop while remaining in the phase continuity among the pulsed interrogation microwaves.

The 9.19-GHz reference frequency is square-wave modulated with the DDS in the synthesizer under control of a PC to conduct the comparison between the reference frequency and the clock transition frequency. In NIM5, the comparison is performed with alternative order of the transition probabilities: R1–B1, R2–B1, R2–B2, R3–B2, R3–B3, and so on (R*i* represents the red tuning transition probability and Bi the blue tuning; the transition probability $\eta = N_4 \ / \ (N_4 + N_3)$ and N_4, N_3 is the number of atoms in $F = 4$ and $F = 3$, respectively). The servo period is reduced to one fountain circle, so the dead time in servo process is reduced in favor of improving the locking stability (reduces Dick effect) [8].

3 Experiments and the preliminary evaluations

NIM5 loads about 7×10^7 atoms in 0.6 s by a direct (1,1,1) OM, the atoms are further postcooled to about 1.5 μK and launched up to 81 cm high from the center of the OM (30 cm above the center of the Ramsey cavity). Atoms loaded by direct MO on NIM5 are 6 to 8 times less than those by MOT, but fortunately with this reduced number of atoms, a good enough stability of the frequency locking is still reached. OM fountain circle on NIM5 is 1.6 s,reduced by half compared with 3 s of MOT NIM4.

It is noted that the launching frequency detuning $\Delta\nu$ and $-\ \Delta\nu$ must be phase-locked to form the stable moving-wave OM, but the average frequency of the two launching frequencies, $(\nu_L + \Delta\nu) + (\nu_L - \Delta\nu) = \nu_L$, needs not equal to the OM loading/cooling frequency ν_P. Instead, it is better to have $\nu_P - \nu_L = 1$ MHz in NIM5.

The typical OM Ramsey pattern with frequency scanning step of 0.1 Hz without average is shown in Fig. 3. A full width half magnitude (FWHM) linewidth of around 1 Hz with signal to noise ratio (S/N) of 400 is realized, and more than 67 fringes can be clearly recognized.

The saturation optical power density for Cs cooling transition of $F = 4$ to $F' = 5$ is 1.1 mW/cm^2. Using the laser optics mentioned above, an OM with 6×11-mW optical power and 26-mm beam diameter is applied to capture more atoms for better S/N. In this operation with saturated optical power density, the number of OM atoms is less sensitive to laser power fluctuations. Higher optical power density may heat the Doppler cooled atoms, so the atom temperature after Doppler cooling can be above the 124 μK of Doppler cooling temperature limit. However, the atoms are further cooled by the postpolarization gradient cooling, and experiment depicts a final temperature of 1.5 μK. In the end, the number of atoms captured is increased and more stable at no sacrifice of atom cooling temperature.

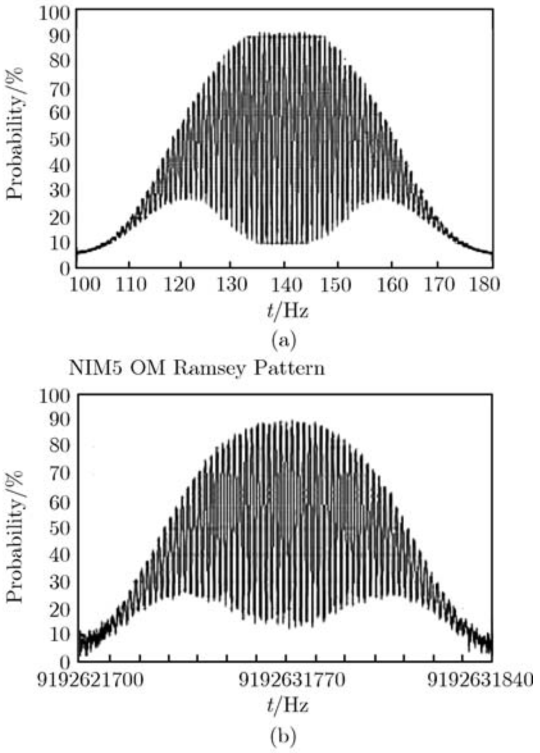

Fig. 3 Typical MOT (a) and OM (b) Ramsey pattern with FWHM of around 1 Hz (frequency scanning step of 0.1 Hz without average).

The day-to-day subcontinuous frequency locking with operation ratio of 99% and a stability of 5×10^{-14} in 10 s (fountain circle of 1.6 s), 3×10^{-15} in 1 d (including the stability of H-maser) is approached in direct OM without using the extra low velocity atom source suggested by, for example, Ref. [9].

For evaluating the frequency shift introduced by atom collisions, the atom density is changed by 3 to 4 times with direct OM by means of controlling the selection RF power. The low-density OM is chosen as the normal operation mode, and only for the collision evaluation, the high-density mode is used.

The latest frequency shift evaluations on NIM5, following the commonly accepted evaluation process [10], is listed in Table 1, and we quote the final combined evaluation uncertainty for NIM5 as 3×10^{-15}.

The C-field was mapped by the magneto-sensitive Rabi transition. The homogeneity of the C-field is less than 1 nT in the height range of 56−82 cm above the OM center.

The atomic density is switched alternatively and quickly between high and low density for atom collision shift evaluations. The zero density frequency is extrapolated according to the least-square fit to the data obtained. The microwave power-related shift is deduced in the similar way but with alternative interrogation microwave powers.

The dominative uncertainty source in Table 1 is the microwave spectrum purity and leakage frequency shift. Figure 4 shows the frequency shifts on NIM5 operating with interrogation microwave power 1, 9, 25, 49, and 81 times to the $\pi/2$ pulse and the curve fitted to these data. We expect that this shift could be eliminated and the related uncertainty reduced when the interference switch or DDS frequency tuning technique mentioned above functions properly before too long.

Table 1 NIM5 accuracy budget (October, 2008).

	Physical effect	Shift (10^{-15})	Uncertainty (10^{-15})	
1	2nd Zeeman	76.2	0.4	H_C=128.0 nT
2	Cold collision	−1.1	0.8	
3	Microwave sractrum purity and leacage	2.1	2.0	
4	Blackbody	−23.2	0.9	Temperature: 51±3 °C
5	Gravitation	3.8	0.1	Above sea: 34.5 m
6	Majorana	0.0	0.1	
7	Light shift	0.0	0.1	
8	Cavity pulling	0.0	0.1	
9	Cavity phase difference	0.0	0.1	Phase difference: 4 μ radian
	Combined	57.8	2.4	

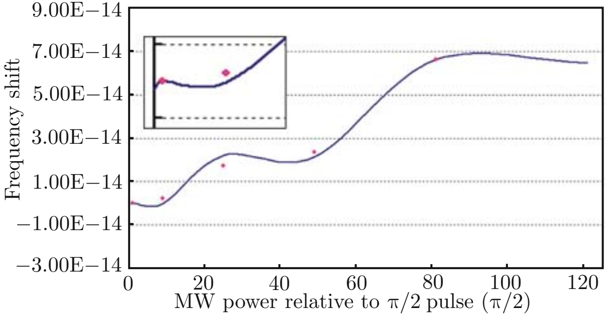

Fig. 4 Evaluation of the microwave purity and leakage frequency shift.

4 Discussion and future work

The NIM5 is expected to resume operation with minor adjustments after its relocation to NIM's new Changping campus, which is 40 km away from the present Hepingli campus.

The NIM5 and NIM4 are going to run in parallel and compare with each other to form the primary frequency standard in China. Since the beginning of 2008, the NIM4 and NIM5 data are used to steer the frequency of H-maser through a phase microstepper to generate the calculated atomic time TA-c (NIM), and the preliminary experiment results demonstrates significantly better stability than that obtained by the traditional Cs clock and H-maser assembly [11].

An experimental frequency transfer fiber system has been set up at NIM. A 1560-nm laser is phase modulated with 5 GHz, and the 10 GHz beat frequency between the two modulation sidebands, traveling through the fiber, is taken as the transferred reference frequency. A stability of $3\times10^{-15}/1000$ s is observed with active compensation of the fiber-induced disturbances [12]. A 60-km fiber transfer linking the NIM Hepingli and Changping campus is under construction.

NIM has built a femtosecond optical comb based on Ti:Saphire laser [13] and acquired another fiber optical comb to establish the bridge between microwave frequency and optical frequency.

NIM started also the construction of an optical frequency standard based on laser cooling strontium (Sr) lattice, and the Sr blue MOT atom clouds were observed in July 2008.

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