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DEVELOPMENT OF CS ATOMIC FOUNTAIN FREQUENCY STANDARD AT CRL

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Abstract - **Communications Research Laboratory (CRL) has been developing a Cesium atomic fountain primary frequency standard. Cs atoms are cooled to below 2μK by both magneto-optical trap (MOT) and polarization gradient cooling (PGC), and launched vertically by moving molasses method. The launched atoms pass through a microwave cavity twice, on the way upward and downward, and give rise to Ramsey resonance. We succeeded to observe narrower than 1Hz Ramsey signal, and tried to lock the microwave frequency to the atomic resonance. This report presents the current status of the development of CRL atomic fountain.**
***Keywords* - atomic fountain, primary frequency standard**

INTRODUCTION

CRL has been operating the optically pumped primary frequency standard named CRL-O1[1,2], whose frequency uncertainty is presently less than 1×10^{-14}. The accuracy evaluation has been performed several times per year, and the data are sent to the BIPM to contribute to the determination of TAI. Further drastic improvement of the frequency accuracy seems to be difficult because of the limit of the measurement time in Ramsey's method for the thermal beam. To obtain the higher frequency accuracy, atomic fountain frequency standards have been developed in many countries. Especially at BNM-SYRTE[3], PTB[4] and NIST[5], the atomic fountain frequency standards have already been operating, whose frequency accuracy is presently about 1×10^{-15}. Aiming at an operational primary frequency standard, CRL also has been developing the atomic fountain frequency standard[6,7]. Our goal in the standard is the frequency uncertainty of 1×10^{-15}.

DESCRIPTION OF CRL ATOMIC FOUNTAIN

A. Physical Package

Our atomic fountain system consists of three parts, laser cooling area, microwave interaction region and detection zone (see Fig.1). The detection zone is located between the laser cooling area and the microwave interaction region. Most of the system are made with non-magnetic metals such as aluminum or copper. The height of total system is about 2m. The laser cooling area consists of a trap chamber with a pair of anti-helmholtz coils (600 turns). This area is surrounded by one layer magnetic shield. The residual magnetic field is compensated by three orthogonal pairs of coils, which are located around the trap chamber. The microwave interaction region contains a C-field coils and a TE_{011} microwave cavity, whose loaded quality factor is about 10000. The whole of this region is surrounded by four-layers magnetic shields, which produce the shielding of order 10^5. The C-field coil and one of the four-layers shields are set inside the high-vacuum chamber, which is surrounded with a non-magnetic heater to control the temperature of the microwave interaction region. The detection chamber has three laser interaction zones where the detection beams irradiate the falling atoms. Two photodiodes, which have a large active area ($1cm^2$), are set

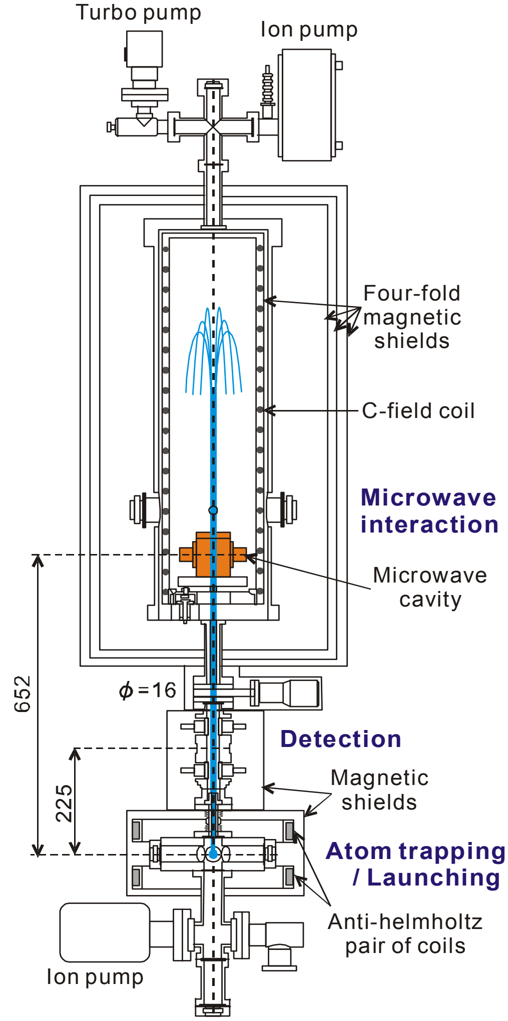

Fig.1 CRL Atomic Fountain

at the upper and the lower zones to observe the fluorescence of the falling atoms, and the middle zone is used for an optical pumping. At present, the selection cavity, which prepares the F=3 atoms, is not installed. By using two ion pumps (20 litters) and two Ti-getter pumps, very high vacuum ($<3\times10^{-8}$ Pa) of the whole system has been achieved.

B. Laser Setup

We use an extended-cavity diode laser (ECDL) as the master laser, whose frequency is locked to Cs D_2 absorption line. To amplify the laser power, three 150mW laser diodes (SDL5422), which provide the cooling laser beams, are injection-locked. The frequency and the power of each laser beam are controlled by an acousto-optical modulators (AOMs). Each laser beam is delivered to the trap chamber through polarization maintaining fiber (PMF). Output port of each fiber has a collimation lens and a quarter-wave plate, which generate the circular-polarized beams of the diameter of 20mm with the power density of at least 5mW/cm^2.

Two more ECDLs are used for repump, optical pumping and detection. By modulation transfer spectroscopy technique, the lasers are locked to the saturated absorption lines of Cesium independently. One laser locked to the F=3-F'=4 transition is used to pump the F=3 atoms back to the F=4 state. It is split into two beams; one is used for the laser cooling and the other is for the detection. The other laser locked to the F=4-F'=5 transition produces the optical pumping beam (F=4-F'=3) and the detection beam (2MHz red-detune to F=4-F'=5). The detection beam is divided into two beams and used to observe the F=4 and the F=3 atoms independently for the normalization. The optical pumping beam and two detection beams are also delivered to the detection zone through PMF. Superpositions of the laser beams are done in the optical fiber.

C. Microwave Synthesizer

For the source of 9.2GHz microwave interrogation, we use a NIST synthesizer[8]. A direct digital synthesizer (DDS) of the microwave synthesizer is phase-locked to the 5MHz of the hydrogen maser, which is linked to UTC(CRL). Using PC control, we make small frequency change in the DDS to tune the microwave with a resolution of less than 1μHz. The output power of the synthesizer is controlled by a power servo with an uncertainty of 0.05dB.

FOUNTAIN OPERATION

Cs atoms are captured in a MOT, then cooled in the optical molasses until the residual magnetic field of the anti-helmholtz coils becomes less than 10^{-6} Tesla so as to avoid that the residual field influences the PGC effect. The atoms are further-cooled to the sub-Doppler temperature by PGC (pre-cooling). To use the full region of the cooling beams for the launch, the further-cooled atoms are at first push down to the lower edge of the horizontal cooling beams by 1-dimensional moving molasses. Then, the atoms are launched upward by 1-dimensional moving molasses. In our system, in order to observe narrower than 1Hz Ramsey fringe, the atoms must be launched with the initial velocity of over 4.4m/s. After giving the atoms the initial velocity, the cooling lasers are back to the PGC detuning and the launched atoms are post-cooled. All the lasers are turned off by AOM and mechanical shutters just before the atoms jump out from the horizontal beams in order to launch the atom straight upward and avoid the light shift.

By using time-of-flight (TOF) technique, the fluorescence, emitted from the falling atoms, is detected at the detection zone, which is located at 18cm above the loading point. From the observed TOF signals for the various initial velocities, we confirm that the equilibrium temperature is below 2μK.

All launched atoms are pumped to the F=3 state by the optical pumping before the microwave interaction. Twice π/2-pulse microwave interactions move the atom in the F=3 state to the F=4 state. At the detection zone, both the F=4 and the F=3 atoms are monitored independently. At the upper detection zone with a standing-wave light field tuned to F=4-F'=5 transition, the fluorescence I_4 emitted from the F=4 atoms is observed. At the lower zone with a superposition of the standing-wave light fields tuned to F=3-F'=4 and F=4-F'=5 transition, the fluorescence I_{all} from both the F=4 and the F=3 atoms is observed. The fraction $P=I_4/I_{all}$ indicates the normalized transition probability, which is independent of the cycle-to-cycle fluctuation of the number of the launched atoms. We observe Ramsey fringe by potting the fraction P against the microwave frequency. With the initial velocity of 4.4m/s, the atoms are launched to a height of 30cm above the microwave cavity (100cm above the loading point), which gives the drift time of 520ms. As a result, the Ramsey signal of 0.96Hz linewidth is observed [Fig. 2].

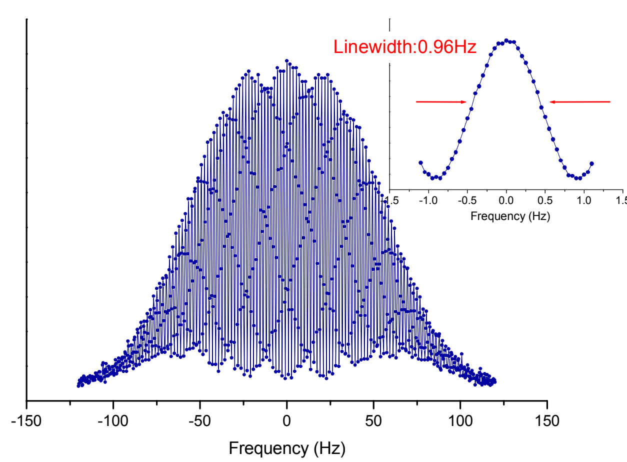

Fig.2 Observed Ramsey Signal with 10 times averaging. The Linewidth of the central peak is 0.96Hz.

Stability

Although the signal to noise (SN) ratio of the observed Ramsey signal is not enough to achieve the frequency uncertainty of the order of 10^{-15}, we made a first trial to lock the microwave frequency to the narrow atomic resonance. At present, we adopt a simple locking method, which gives a constant frequency step by comparing the signal intensities at the frequencies of $f_0-\Delta\nu/2$ and $f_0+\Delta\nu/2$ where f_0 is the microwave frequency, and $\Delta\nu$ is the linewidth of the Ramsey fringe. The operation is, when the signal at the lower frequency is stronger than that at the upper frequency, f_0 is adjusted lower by the amount of the constant frequency step, and vice versa. Fig. 2 shows the frequency stability $\sigma_y(\tau)$ of the present CRL fountain. Because of the constant step, the short-term stability (less than 100s) looks better than the actual. However, the stability at longer than 100s is independent of the constant frequency step, which means that the result is reliable. A linear fitting shows the frequency stability of about $1\times10^{-11}/\tau^{1/2}$. The present stability is due to the low SN ratio of the observed Ramsey signal. Therefore, as the SN ratio increase, the frequency stability will be better.

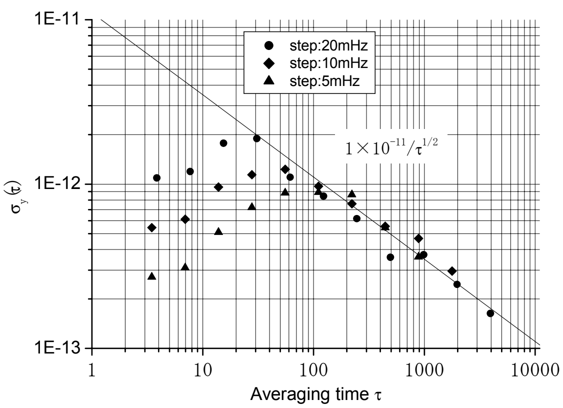

Fig. 3 Allan Variance $\sigma_y(\tau)$. So far, the frequency stability is $1\times10^{-11}/\tau^{1/2}$.

Summary

CRL has been developing the Cs atomic fountain primary frequency standard. We have succeeded to observe narrower than 1Hz Ramsey signal, and tried to lock the microwave to the atomic resonance. So far, we obtained the frequency stability of about $1\times10^{-11}/\tau^{1/2}$. Further development to improve the SN ratio of the Ramsey signal is required.

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