3-2-2 Development of Atomic Fountain Primary Frequency Standard at CRL

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Communications Research Laboratory has been conducting the development a Cesium atomic fountain primary frequency standard. Cs atoms are cooled to below 2 μK by a magneto-optical trap and polarization gradient cooling, 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 whose linewidth is less than 1 Hz. The atomic fountain standard based on the cold atoms is expected to achieve the uncertainty of the order of 10^{-15}. We also have been developing the atomic fountain to aim at an operational primary frequency standard with the frequency uncertainty of 1×10^{-15}. In this chapter, we report the present status of development of atomic fountain at CRL.

Keywords
Atomic fountain, Primary frequency standard, Laser cooling, Polarization gradient cooling, Ramsey fringe

1 Introduction

The Atomic Frequency Standards Group of the Communications Research Laboratory has been developing a primary frequency standard with the aim of contributing to the enhancement of the accuracy of International Atomic Time (TAI) and Japanese Standard Time (JST). A primary frequency standard is a device capable of accurately determining the length of the second, the fundamental unit of time; research on such devices is currently underway throughout the world.

As of 2003, there are only three types of primary frequency standard contributing to the accuracy evaluation of International Atomic Time: the magnetic selection type, the optically pumped type, and the atomic fountain type. At the CRL we have been working on developing primary frequency standards of the magnetic-selection type (CRL-CS1) and of the optically pumped type (CRL-O1) [1] (frequency accuracy of CRL-O1: 1×10^{-14} or better). While magnetic selection and optically pumped frequency standards both employ an atomic beam, the atomic fountain frequency standard uses "cold atoms;" i.e., atoms whose velocities are significantly reduced. This type of frequency standard is expected to yield a frequency accuracy in the order of 1×10^{-15}, one order of magnitude better than that of conventional standards using an atomic beam.

In recent years, research on the atomic fountain standard has been carried out in a number of countries, with actual operations underway in France, Germany, the U.S., and elsewhere[2]-[4]. In our capacity as a laboratory group contributing to the overall enhancement of the accuracy of TAI and JST, we are also developing an atomic fountain primary frequency standard, with the ultimate goal of achieving accuracy of 1×10^{-15}.

1.1 Structure of atomic fountain primary frequency standard

The structure of the atomic fountain frequency standard is as illustrated in Fig.1 (left-hand figure). The process of operations of the atomic fountain standard is as shown below.

(1) Cesium atoms are laser-cooled three-

dimensionally.

(2) An ensemble of cold atoms is launched vertically by a laser beam.

(3) The launched atomic ensemble initially interacts with a microwave in a microwave cavity placed in the path of the atoms.

(4) Following interaction with the microwave, the atomic ensemble continues on its trajectory, subsequently reversing and beginning to fall by the force of gravity.

(5) As it falls, the atomic ensemble again passes through the microwave cavity, interacting with the microwave again.

(6) These falling atoms are detected.

Thus, the launched atomic ensemble interacts with the microwave twice, at the time of launching and at the time of falling, giving rise to Ramsey resonance[5]. The linewidth of the Ramsey fringe is very narrow, and the center frequency of this signal is utilized as the reference signal of the standard. Since the behavior of the atoms that are launched by the laser beam and then fall by the force of gravity resembles that of a fountain of water, this mechanism is referred to as "genshi sen" in Japanese and as the "atomic fountain" in English.

1.2 Comparison between atomic fountain standard and other primary frequency standards

Although frequency standards include hydrogen maser, commercial cesium frequency standard, rubidium frequency standard, these devices are appropriately called "clocks" (or atomic clocks), rather than primary frequency standards. In this section we will focus specifically on primary frequency standards: the magnetic selection type, the optically pumped type, and the atomic fountain type. In particular we will demonstrate that the most significant difference between conventional frequency standards (magnetic selection and optically pumped types) and the atomic fountain frequency standard lies in the employment of an atomic beam in one case and in the use of "cold atoms" in the other.

This difference leads to different appearances of the overall devices. The atomic beam frequency standard is a transverse device in which atoms move horizontally (see the right-hand illustration in Fig.1), whereas the atomic fountain frequency standard is a longitudinally oriented device in which atoms move vertically (see the left-hand figure in Fig.1).

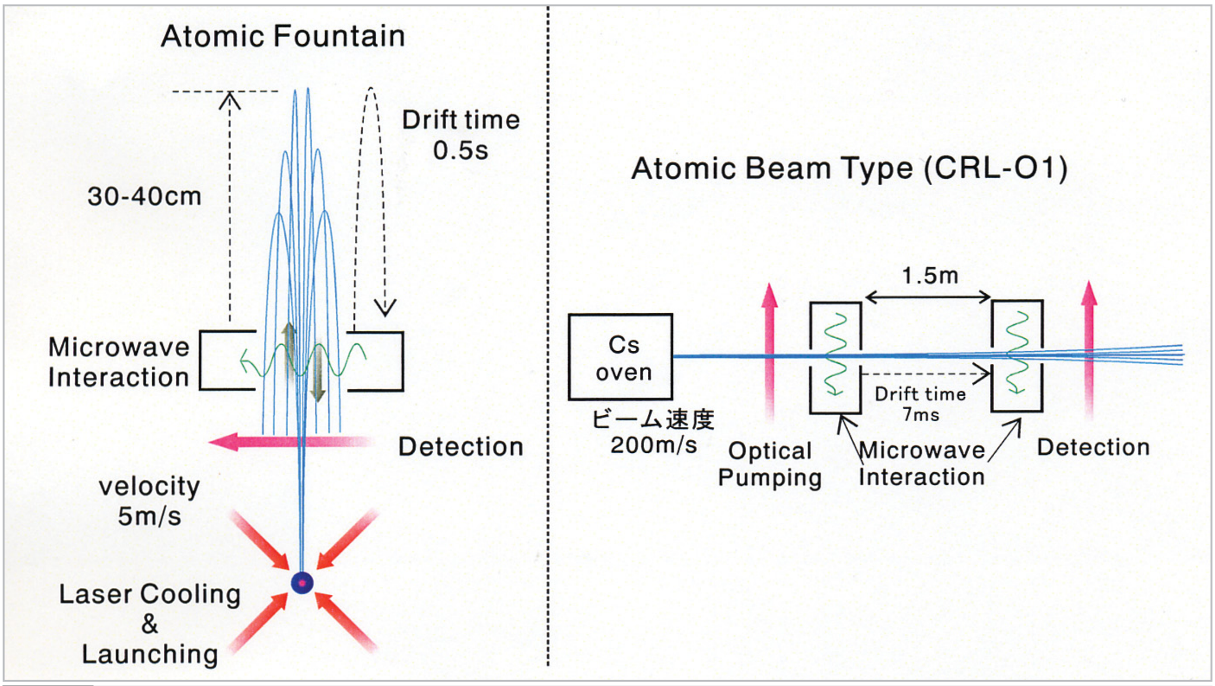

Fig. 1 *Schematic diagrams of the atomic fountain standard and the atomic beam standard*

The frequency stability of the primary frequency standard is expressed by formula (1), which indicates that with decreasing signal linewidth, stability becomes higher[6].

$$\sigma_y(\tau_m) \propto \frac{\Delta\nu}{\nu_0 \cdot (S/N)} \cdot \frac{1}{\sqrt{\tau_m}} \qquad (1)$$

where $\Delta\nu$ is the linewidth of the signal (full width at half maximum), ν_0 is the clock frequency of the atom, (S/N) is the signal-to-noise ratio for an averaging time of 1 sec, and τ_m is the measurement time. The Ramsey resonance method is a technique whereby a time interval is secured between the first and second interactions of the atoms with the microwave, and the resultant signal, with a linewidth dependent on the time interval, is observed (refer to Article **3-1** and Appendix for Article **3-2-1** of this issue).

The transition probability of the Ramsey fringe near the resonance frequency is given by formula (2.1), and the linewidth of the core of the signal is expressed by formula (2.3)[7].

$$P(\tau) = \frac{1}{2}\sin^2 b\tau[1+\cos\{(\omega_0-\omega)T\}] \qquad (2.1)$$

$$b = \frac{\mu_B B}{\hbar} \qquad (2.2)$$

$$\Delta\nu = \frac{1}{2T} \qquad (2.3)$$

where ω_0 is the resonance frequency of the atom, ω is the microwave frequency, μ_B is the Bohr magneton, B is the magnetic flux density of the microwave, τ is the period of time during which the atom passes through the cavity, and T is the drift time (the time interval between the first and second interactions with the microwave). Formula (2.3) indicates that the Ramsey fringe becomes narrower with increasing drift time T, corresponding to increasing the frequency stability. For the magnetic selection and the optically pumped frequency standards, using an atomic beam, the velocity of the atom passing between two cavities (separation of 1.5 m) is fast (200 m/s), with a drift time as short as approximately 7 ms. However, the atomic fountain frequency standard using cold atoms can secure a drift time of 500 ms or higher, approximately 100 times longer than the atomic-beam type, by launching atoms at a very low velocity (5 m/s) vertically up to a height of approximately 30 cm above the microwave cavity. This long drift time reduces the linewidth of the Ramsey fringe to less than 1 Hz, considerably increasing the frequency stability.

On the other hand, the signal weakness presents a drawback of the atomic fountain frequency standard. This weakness results from the fact that the number of atoms contributing to the signal is small, resulting in a signal-to-noise ratio approximately one-tenth that of the atomic-beam type. Moreover, the atomic beam frequency standard can eject atoms continuously, whereas the atomic fountain type is of the pulse-operation type, launching each atom after the previously launched atom has fallen. This pulse operation amplifies the effect of the high-frequency components in microwave phase noise, resulting in degradation of the frequency stability. This effect, referred to as the Dick effect[8], does not occur in the magnetic-selection or optically pumped frequency standards that employ continuous operation. However, even with these combined disadvantages, the atomic fountain standard yields frequency accuracy ten times greater than conventional atomic beam standards, because the linewidth of the signal in the former is one hundred times narrower than that in the latter.

The frequency generated by the primary frequency standard can shift from the defined value because of various physical and/or engineering factors. Therefore, in order to calculate the desired defined value, it is necessary to estimate various frequency shifts and subtract these shift quantities from the generated frequency. Uncertainty is present in each of these estimated shift quantities, and the sum of these uncertainties determines the final accuracy of the primary frequency standard. It is indispensable, in the development of the primary frequency standard, to be able to estimate these frequency shifts. Here the features of the atomic fountain frequency standard will also be described specifically from the standpoint of frequency shift.

The advantages of the atomic fountain frequency standard include the following: For details of the specific shift factors mentioned, refer to Article **3-2-1** of this issue.

- Since cold atoms with low velocities are used, second-order Doppler shift is small.
- Since the linewidth of the observed signal is narrow, shifts resulting from non-uniformity in the magnetic field and the microwave cavity are small.
- Since only one cavity is used, shift resulting from phase difference inside the cavity is small.

Through the use of cold atoms, almost all frequency shifts are minimized, with corresponding uncertainties reduced to a magnitude of less than 10^{-15}. On the other hand, while nearly all of the frequency shifts are reduced, collisional shift due to collision of the cold atoms becomes large. This is attributed to the fact that with decreasing atomic temperatures, the de Broglie wavelength will become large, with the collision cross section increasing accordingly. Estimation of this collisional shift brings significant uncertainty, and in the case of the atomic fountain frequency standard, it may safely be said that the magnitude of the uncertainty of this collisional shift determines the limit of the standard. It is difficult to minimize collisional shift without hampering stability; nevertheless, the overall reduction in shift factors indicates the relative strength of the atomic fountain standard.

1.3 History of development of atomic fountain standard at the CRL

Development of a primary frequency standard requires a significant store of specialized knowledge, covering areas such as vacuum technology, laser technology, electric-circuit technology, and computer control. In particular, with the atomic fountain frequency standard, technology relating to the formation and launching of cold atoms is critical. Of primary importance is the technology required to launch a great number of atoms and then to capture them as they fall by the force of gravity. At the CRL we have been working to acquire these basic technologies, with a focus on laser cooling and highly efficient launching of cold atoms, using a small-size prototype device[10][11], concurrently working to develop a full-size atomic fountain device capable of operation as a primary frequency standard [12][13]. In this paper, we report on the present status of development of the full-size atomic fountain frequency standard.

2 Structure of the CRL atomic fountain primary standard

2.1 Object and function of each part

Fig.2 presents a diagram of the CRL atomic fountain frequency standard. Broadly speaking, the atomic fountain system consist of three sections: a trap section for generating and launching cold atoms, a microwave interaction section where the launched cold atoms interact twice with the microwave, and a detection section to detect the falling atoms that interacted with the microwave. Since a non-uniform magnetic field gradient in the trap section reduces the efficiency of atom launching and a non-uniform magnetic field in the microwave interaction section causes the frequency shift of the observed signal, most of the device is made of non-magnetic materials, such as copper and aluminum.

The trap section is composed of a chamber where six laser beams propagate three-dimensionally to realize an overlap region and an anti-Helmholtz coil designed to form a quadrupole magnetic field (a pair of coils in which electrical currents flow in opposite directions); the entire trap section is surrounded by a single magnetic shield. Inside the shield, correcting coils are disposed in the X, Y, and Z directions to cancel the effect of geomagnetism. The trap chamber is equipped with a reservoir in which cesium atoms are sealed, and the amount of cesium atoms that are fed into the chamber is regulated by temperature control of the reservoir.

The detection section is composed of a

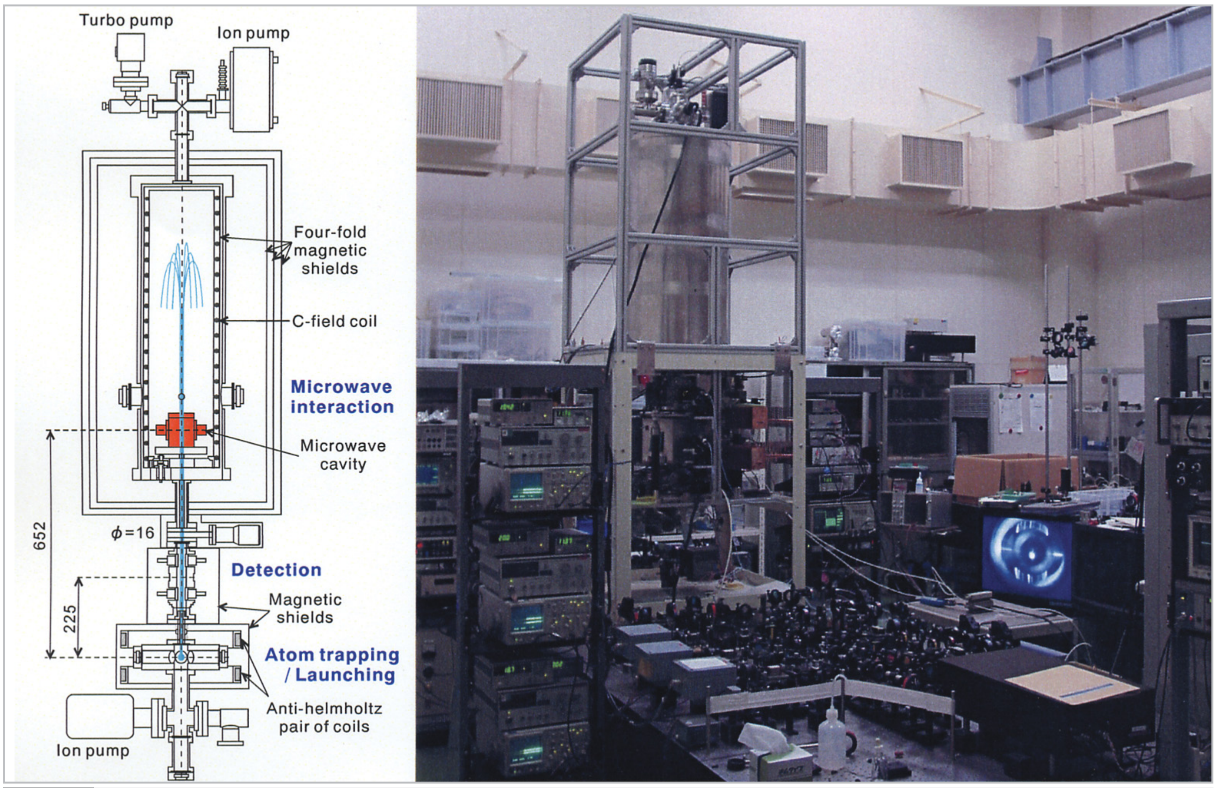

Fig.2 *CRL's atomic fountain primary frequency standard*

view port for the probe laser beam and a special view port for a detector can be mounted to observe fluorescence. A photodetector (PD) made of Si (silicon) with an active area of 1 cm^2 is mounted on the special view port; this device observes the fluorescence emitted by the cesium atoms that fall after interacting with the microwave.

The microwave interaction section is composed of a C-field coil to separate the different magnetic sub-levels of the cesium atom's ground state and a microwave cavity to excite the clock transition of cesium atoms. The entire microwave interaction section is surrounded by four-layer magnetic shields to block the effects of external magnetic fields.

Since only the transition $\Delta m_F = 0$ of an atom with a magnetic quantum number of $m_F = 0$ generates the required reference signal of the frequency standard, the direction of the C-field must be parallel to the direction of the magnetic field of the microwave. In the case of CRL atomic fountain, since the direction of the C-field lies in a vertical plane, the microwave cavity is used in the TE_{011} mode (in which the magnetic-field component of the microwave inside the cavity is aligned vertically)[8]. The Q factor of the microwave cavity currently used is approximately 10,000.

Collision between the ensemble of atoms and residual background gas while the atom interacts with the microwave will degrade the S/N ratio, and hence very high vacuum is required in the microwave interaction section. We employed a Ti getter pump, in addition to a turbo-molecular pump (roughing vacuum pump) and an ion pump, to achieve a high vacuum of less than 3×10^{-10} torr. In order to prevent the cesium atoms in the trap section from seeping into the microwave interaction section, we designed all sections such that the spaces between each section are separated by narrowing diameters of holes to 1 to 1.5 cm. Since the diameters of these holes, through which the atoms must pass, are very narrow with respect to the flight distance of the atoms (a round-trip flight of approximately 2 m from launching to detection), accuracy of 1 mrad is required to launch the atoms and force them through the microwave cavity for observation in the detection section.

2.2 Laser optical system

As mentioned in Section **1.2** in this paper, the signal weakness that results from the relatively small number of atoms represents a drawback of the atomic fountain standard. Accordingly, a laser light source was modified to yield a higher output, in order to increase the number of atoms that could be trapped, thus increasing signal strength. Since stability of frequency and optical power of the light source are important factors in the stable operation of the standard, semiconductor lasers featuring stable frequencies and power were used. Fig.3 shows a diagram of the optical system for the atomic fountain.

We prepared a high-power light source by injection locking three high-output (150 mW) semiconductor lasers. A portion of the main laser beam is injected into three slave lasers, whereby oscillating frequencies of all slave lasers are locked to the oscillating frequency of the master laser. A stable extended-cavity diode laser with a narrow oscillating linewidth (500 kHz) is used as the main laser, and the master laser is frequency-stabilized to an absorption line ($F = 4 \rightarrow F' = 5$) of the cesium atom.

It is necessary to shift the frequency of the laser by about 1 MHz to 60 MHz within a short time (a few μs) from one process to another, from the initial cooling of the cesium atom to the second cooling to launch. The laser-frequency shift is performed using an acousto-optic modulator (AOM). An AOM through which a laser beam passes once will change the optical axis of the laser when the modulation frequency of the AOM is changed; thus we adopted the Cat's Eye configuration, in which the laser beam passes through the AOM twice, such that the optical axis does not change with modulation frequency. When the atoms are launched, the laser beam must be frequency-shifted in the upward and in the downward directions (± Z directions) separately; independent AOMs are used for the upward beam and for the downward beam. Since the laser beams counter-propagating in the horizontal direction may be of the same frequencies with respect to each other, the laser beam is frequency-shifted by a single AOM and is then reflected by a mirror to form a counter-propagating laser beam. Two sets of such beams were prepared for the horizontal X and Y directions.

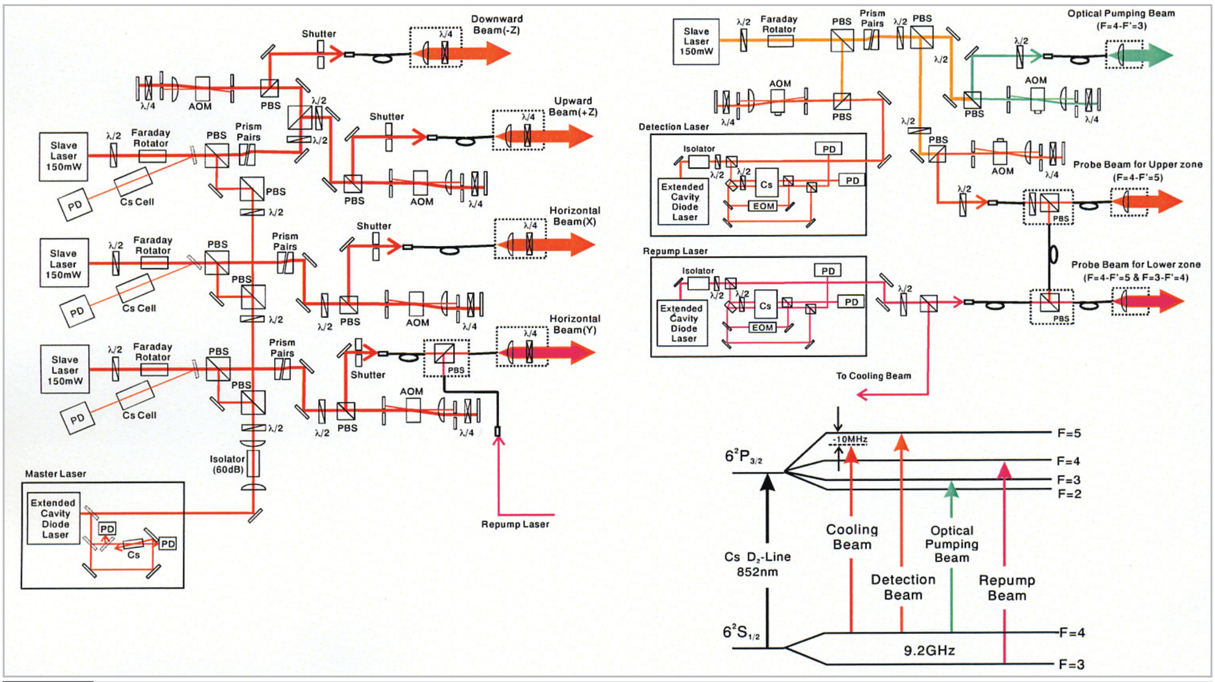

Fig.3 Laser optical system for atomic fountain and energy level diagram of cesium atom

Not only does the AOM change the frequency, but it also changes the optical power of the cooling beam. When the cooling beam is to be turned off, this is done by reducing the efficiency of the AOM. Since the laser light, however, cannot be completely turned off solely with the AOM, a mechanical shutter is driven simultaneously to block the light completely.

After passing through the AOMs, four laser beams are guided to the trap chamber via optical fiber. Each optical fiber not only prevents the laser beam power from fluctuating due to air turbulence, but also acts as a spatial filter for the correction of spatial modes. A $\lambda/4$ plate is attached to the exit facet of each optical fiber, making it possible to obtain the circularly polarized laser beam necessary for laser cooling. A total of four cooling beams are prepared: one upward beam, one downward beam, and two horizontal beams. Each beam has a final diameter of 2.5 cm, power of about 10 mW/cm^2, and a Gaussian distribution. The laser beams in the horizontal direction are reflected by mirrors, so that the cesium atoms are finally irradiated by laser beams from six directions.

Laser cooling requires a repump beam ($F = 3 \rightarrow F' = 4$) for pumping the atoms back to the initial state. Another extended-cavity diode laser was prepared for the repump beam, which was superposed on the cooling beam inside the fiber and made to irradiate the cesium atoms. In addition, another extended-cavity diode laser was prepared for optical pumping ($F = 4 \rightarrow F' = 3$) and for detection ($F = 4 \rightarrow F' = 5$) (for details, refer to Section 3.3 of this paper).

2.3 Microwave synthesizer

Even when a long drift time is secured and a signal with a narrow linewidth is successfully obtained, if the accuracy of the frequency itself is poor in measurement of the center frequency of the signal, the measurement will be of little value. In order to measure the center frequency accurately, a stable microwave generation apparatus is necessary. As the hydrogen maser is known as a frequency standard with excellent short-term stability (within approximately one day), we prepared a 9.2-GHz band microwave synthesizer using a hydrogen maser as a source oscillator. This synthesizer has been developed for a space clock[14] by the NIST of the United States, and features a stability as high as 5×10^{-17} over 10,000 sec. The 9.2-GHz synthesizer is composed of 5-MHz and 100-MHz voltage-controlled crystal oscillators (VCXOs), a 6.4-GHz yttrium iron garnet (YIG) oscillator, and a 407-MHz direct digital synthesizer (DDS), with all of them phase-locked to the 5-MHz output of a commercial hydrogen maser. The output of the hydrogen maser is time-compared with UTC (CRL) (Coordinated Universal Time at CRL: refer to Article **2-1** of this issue) every four hours, and the UTC (CRL) is compared with UTC at the BIPM (International Bureau of Weight and Measures) every five days. After several mediating processes, ultimately the value provided by the atomic fountain standard at the CRL is compared with the BIPM value, contributing to the overall enhancement of the accuracy of UTC and TAI.

The oscillating frequency of the synthesizer can be varied with a resolution of 1 μHz by DDS control via a PC, and output may be stabilized with uncertainty of less than 0.05 dB by a power servo.

3 Component technologies required for atomic fountain frequency standard

3.1 Magneto-optical trap and polarization gradient cooling[15]

To reduce the velocity of cesium atoms moving at several hundred m/s at room temperature, two kinds of laser-cooling methods are employed: the magneto-optical trap (MOT) and polarization gradient cooling (PGC). In the development of the atomic fountain, laser cooling technology is critical, to cool the atomic ensemble to the full extent possible while minimizing the reduction in the number of atoms that can be captured. Laser cooling parameters must therefore be optimized to ensure a maximum number of atoms observable at the detection section.

MOT is a method of cooling atoms while the atoms are maintained in a trap zone by making an ingenious use of the Doppler cooling effect and the interaction of the atoms with the magnetic field. If, in the interaction with a laser beam, an atom absorbs and emits one of the laser beam's photons, the atom receives the momentum of one photon $p = h/\lambda$ (h is Planck's constant and λ is the wavelength) in the direction of propagation of the laser beam. The atom then receives radiation pressure in the direction of propagation of the laser beam, with the corresponding deceleration expressed by $\Delta v = p/M$ (where M is atomic mass). In the case of the cesium atom, the rate Γ at which the atom absorbs and emits one photon in one second is in the order of 10^8, and consequently the deceleration of the atom due to its interaction with the laser beam $\Gamma\Delta v$ becomes approximately 10^5 m/sec^2. This represents a force of 10,000g (10,000 times greater than gravitational acceleration), attesting to the intensity of the force imposed on the atom by the laser beam. If the interaction of the atom with the laser beam continues, the atom will be subject to high radiation pressure from the laser beam and will be rapidly deflected in the direction of propagation of the laser beam. The frequency of the laser beam is therefore set slightly lower than the resonance frequency of the atom. Then, as a result of the Doppler effect, only the atoms flying toward the laser beam will interact with the beam; these will be pushed back in the direction of propagation of the laser beam. Conversely, atoms not flying toward the laser beam will not resonate with the laser beam and will receive no radiation pressure.

Doppler cooling refers to a technique whereby atoms are irradiated from six directions with laser beams at frequencies slightly lower than the resonance frequency of the given atom; the atoms are then collected at the point where all laser beams are overlapped. An atomic ensemble bound only by laser beams as described above is called "optical molasses." This state of optical molasses cannot sustain itself for a long time, and if nothing is done, it will fall by the force of gravity. A method is therefore required that will provide position-dependent irradiation pressure. An anti-Helmholtz coil is added to a three-dimensional Doppler cooling configuration that cools atoms from six directions. Due to the quadrupole magnetic field formed by this anti-Helmholtz coil, a magnetic field gradient is formed such that no magnetic field is present at the core and the magnetic field increases with increasing distance from the center. Due to the characteristics of this magnetic field gradient, the resonance frequency of the atom is subjected to a greater Zeeman shift with increasing distance from the center. If any of the six different counter-propagating laser beams are set to feature mutually orthogonal circular polarization (σ^+ and σ^-), atoms located further from the center are more likely to interact with the laser beams (and thus likely to receive radiation pressure), while atoms in the core will not interact with the laser beams (thus receiving no pressure). Conse-

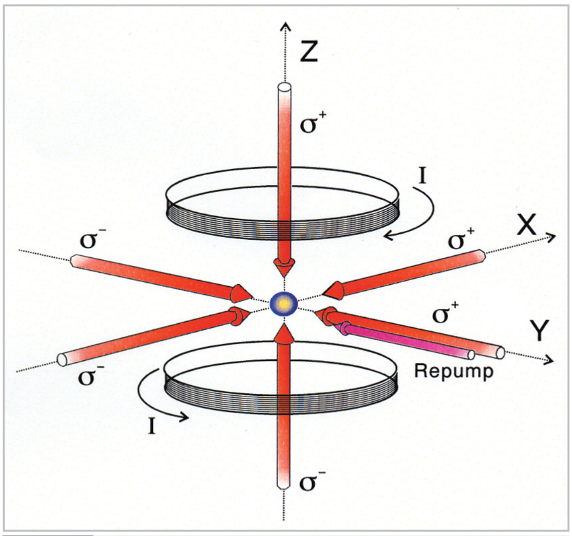

Fig.4 *Magneto-optical trap (MOT)*

The cooling laser beams propagate from six directions to realize the overlap region at the center of the anti-Helmholtz coil (a pair of coils in which currents flow in opposite directions). Counter-propagating beams consist of mutually orthogonal circularly polarized light (σ^+ and σ^-).

quently, the atoms are collected in the core, where the magnetic field is zero. The MOT technique with a magnetic field gradient thus provides a Doppler cooling effect with positional dependency.

Fig.4 shows the laser cooling configuration in the CRL atomic fountain device. Mutually reversed currents are made to flow in the opposing coils to form a quadrupole magnetic field of about 10 Gauss/cm, and cooling beams are made to irradiate toward the center of the magnetic field from six directions; any counter-propagating beams feature mutually orthogonal circular polarizations. As mentioned in Section **2.2** in this paper, laser cooling requires a repump beam to restore atoms forced to another level by the cooling beam to the initial state (see the energy level diagram of Fig.3), the laser beam F = 3 (F' = 4 is made to irradiate toward the center of the trap. In this state, if the frequency of the cooling beam is set to a value detuned approximately −10 MHz from the resonance line of the cesium atom (F = 4 → F' = 5), cesium atoms are trapped in the center of the laser beams and can be cooled to several tens of cm/s (several hundred μK) (i.e., to the Doppler limit temperature). The lower the resultant temperature, the smaller the diffusion of atoms in the horizontal direction when being launched, and the more intense the detected signal strength. In the case of the CRL atomic fountain, atoms must be launched at an initial velocity of about 4.5 m/s in order to obtain a Ramsey fringe of less than 1 Hz, and the time from launch to detection is approximately 1 s. If the arrival temperature of the cold atoms is roughly the Doppler limit temperature, an atomic ensemble confined in a diameter of a few mm will spread to several tens of cm, and consequently the atoms detectable at the detection section will become significantly reduced. Atoms initially slowed by MOT thus require further cooling.

Fig.5 shows a conceptual diagram of PGC. The cooling laser beams, consisting of two counter-propagating beams with mutually orthogonal polarizations, form a standing wave whose polarization state varies with position (where position is a function of the wavelength). With this configuration, the energy state of the atom will split off by the AC Stark effect, and its sub-levels will undergo energy shift depending on the polarization state.

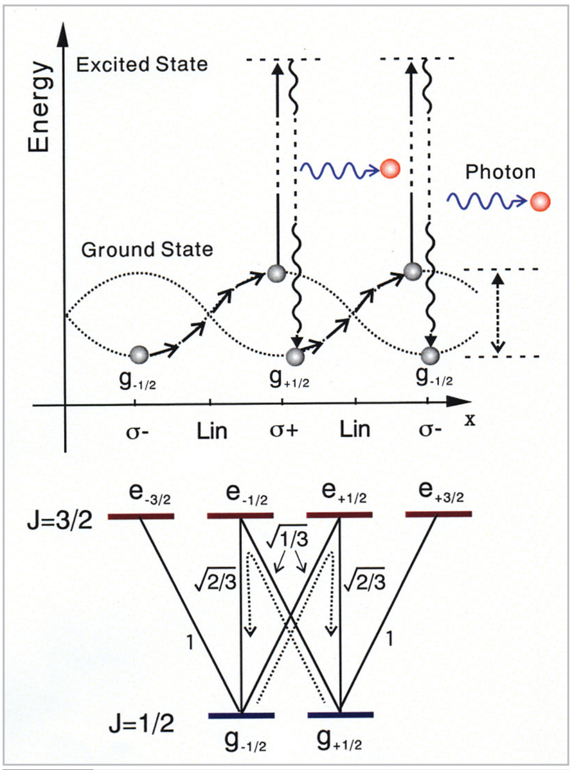

Fig.5 *Mechanism of polarization gradient cooling (PGC)*

(Upper figure) The atom emits energy equivalent to one photon in a single process of absorption and emission.
(Lower figure) Transition probability between energy sub-levels

The transition probability between the sublevels is different for each transition, as can be seen in Fig.5. Therefore, an atom moving within a standing wave featuring a polarization state that varies with position will exhibit absorption and emission characteristics according to the polarization state at the given atomic position and the transition probability. For example, an atom in the $g_{-1/2}$ state will transit to the $e_{+1/2}$ state in a location with a polarization state of σ^+, and an atom excited to the $e_{+1/2}$ state will be relaxed to the $g_{+1/2}$ state, in accordance with the transition probability.

At this point, the atom converts energy

corresponding to the difference between the $g_{-1/2}$ state and the $g_{+1/2}$ state into an emitted photon. The atom in the $g_{+1/2}$ state emits another photon when it reaches a location at which polarization is σ^-. In this way, an atom moving in a standing wave with the polarization gradient will discharge kinetic energy to individual photons, finally releasing the internal energy until it cannot overcome the required splitting energy between sub-levels.

PGC therefore represents a cooling method that makes use of spatial variation in transition probability between sub-levels of a hyperfine structure, a technique that can theoretically cool atoms to the photon recoil temperature (for the cesium atom, approximately 200 nK).

In the case of the atomic fountain, we set the cooling limit around several cm/s (a few μK) to minimize the number of atoms lost in the cooling process. Since the strength of the magnetic field in the trap zone must be less than 10 mGauss (the force of geomagnetism is approximately 400 mGauss) in order to obtain the PGC effect, it becomes very important to eliminate geomagnetism through the use of correction coils disposed around the trap chamber. Moreover, the PGC cooling effect depends on the optical power of the trap beam and on detuning from the resonance line. We have confirmed that when the power of the laser beam is reduced by half and the frequency of the laser is detuned by about −60 MHz, atoms can be cooled efficiently without reducing the number of atoms. Optical power reduction during PGC is performed via adjustment of the diffraction efficiency of the AOM; detuning of −60MHz is accomplished by modifying the locking point of the master laser.

Laser cooling forces all of the cesium atoms into the F = 4 state of the ground level of the hyperfine structure. In an optically pumped standard frequency (the CRL-O1, for example), all of the atoms are gathered into one of the two energy levels of the hyperfine structure (in the case of the CRL-O1, the F = 3 level), leading to greater signal strength than available with a magnetic-selection frequency standard (refer to Article **3-2-1** in this issue). In the case of the atomic fountain, laser cooling process places all atoms in the same state, in addition to slowing the atoms.

3.2 Launching and TOF signal observation

Launching of the cold atoms is performed by detuning the upward laser frequency and the downward laser frequency, this method is called "moving molasses (MM)" technique. In the MM method, if the upward laser beam is positively detuned (+δ) and the downward laser beam is negatively detuned (-δ), the optical potential moves upward, and the atomic ensemble confined in the optical potential gains an initial velocity in the upward direction. This method provides the atomic ensemble with initial velocity while allowing the ensemble to remain cool (i.e., without giving the excess heat); this is because a MOT state is maintained within a coordinate system in which the atom is viewed as having upward velocity. The initial velocity is given by $V_0 = \lambda \cdot \delta$ (λ is the wavelength of the laser light; equal to 852 nm in the case of cesium atom),

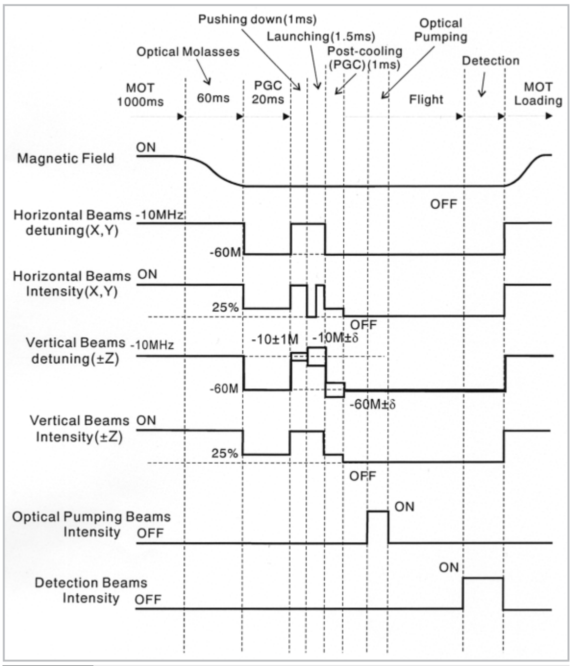

Fig.6 *Timing chart for trapping, cooling, launching, and detection*

and detuning of approximately ±6 MHz becomes necessary to provide an initial velocity of 5 m/s. Frequency detuning in MM is performed by a change in the AOM drive frequency.

Fig.6 shows a timing chart for the capture, cooling, launching, and detection of cesium atoms. Although it is necessary to turn off the MOT trap coil when PGC is initiated, it is difficult to block the magnetic field rapidly due to the inductance of the coil. Therefore, the effect of the residual magnetic field in the MOT coil is avoided by placing the optical molasses process after the MOT step. Once the effect of the magnetic field of the MOT coil dissipates, PGC is performed to cool the atomic ensemble further before launching (pre-cooling). The atoms cooled to below a few μK by this PGC are made to move downward temporarily, and are subsequently launched vertically by the upward MM. Once initial velocity has been imparted to the atoms, the laser beam is changed to the PGC state and cooling is carried out again. Post-cooling is performed until just before the atoms are forced off the horizontal laser beams.

The atoms are moved downward temporarily before launching in order to maximize the time during which the launched atoms move from the lowermost part of the laser beam to the uppermost part (thus lengthening the interaction of the atoms with the laser beam); this in turn enhances the post-cooling effect. Since the switching of the six laser beams must be synchronized within a margin of a few μs, all switching timing is handled via PC.

In order to evaluate the efficiency of cooling and launching, we observed the time-of-flight (TOF) signal of cold atoms by inserting a probe beam into the detection section (approximately 18 cm above the center of the trap section). The launched cesium atoms are passed through the microwave cavity; in this case the microwave is not excited, as the purpose is to verify the efficiency of launching. Fluorescence emitted by the falling atoms when crossing the probe beam is observed by a silicon PD oriented orthogonally to the probe beam. The probe beam is reflected by a mirror to form a standing wave. The atom thus emits fluorescence as it crosses the probe beam.

Fig.7 shows the observed TOF signal. The horizontal axis represents the elapsed time after launch, i.e., the point at which the launched atom, now falling, crosses the probe beam. The value under a given signal in the figure represents the detuning frequency of the moving molasses. The larger the detuning, the larger the resultant launching velocity. Fig.7 clearly shows that as the initial launching velocity is increased, the atom takes longer to fall. The value of the launching velocity and the arrival time agree well with theoretical values, which indicates that the launching of atoms was successfully controlled with high accuracy.

Further, linewidth is determined by fitting the Gaussian curve to the obtained TOF signals, and the diffusion velocity of the atomic ensemble is calculated from the arrival time and the linewidth of the signals. It was thus confirmed that cesium atoms were successfully cooled to below 2 μK by a combination of MOT and PGC, representing atomic cooling by a power of eight, from 300 K (room temperature) to 2 μK.

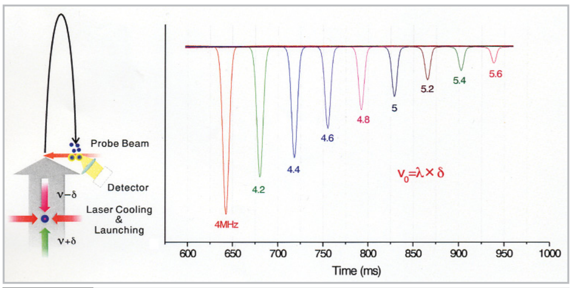

Fig.7 *Observed TOF signal*

The value under the signal indicates the detuning frequency of moving molasses. Due to inverting amplification, the signal is facing downward.

3.3 Observation of Ramsey fringe

Following determination of the efficient cooling and launching of cesium atoms, the Ramsey fringe was observed by exciting the microwave in the microwave cavity. As mentioned in Section **2.1** in this paper, since the reference signal of the frequency standard is a microwave emitted from $\Delta m_F = 0$ transition of the magnetic quantum number $m_F = 0$ atoms, a magnetic field of less than 1 mGauss is generated by the C-field coil in order to separate the different sub-levels of the ground state of the cesium atom. Moreover, the formulas (2.1) and (2.2) indicate that the Ramsey fringe reaches maximum at the condition of $b\tau = \pi/2$. In the case of the atomic fountain frequency standard, where the atomic velocity is slow, the time τ required for the atom to pass through the cavity is long (10 ms); as a result the power of the microwave to be fed to the cavity may be as small as −65 dBm (0.3 nW).

Fig.8 shows a schematic drawing of the interaction of the launched atomic ensemble with the microwave. By laser cooling, all of the cesium atoms are brought into the $F = 4$ state of the ground level of the hyperfine structure. The launched atoms in the $F = 4$ state resonate with the laser beam ($F = 4 \rightarrow F' = 3$) at the detection section, are excited to the excited $F' = 3$ state, and are subsequently brought into the $F = 3$ state of the ground state. This process is referred to as optical pumping. Through this process, the launched atoms are all placed in the $F = 3$ state before interacting with the microwave.

If the atoms could all be placed in the $F = 3$ state of $m_F = 0$ through the introduction of a selection cavity to the apparatus, the optical pumping process would be unnecessary. At present, because a selection cavity is not employed, the launched atoms are brought in the $F = 3$ state by optical pumping. These atoms continue to fly, and interact with the microwave twice. Through this double interaction with the microwave in the cavity, some of the atoms in the $F = 3$ state make the transi-

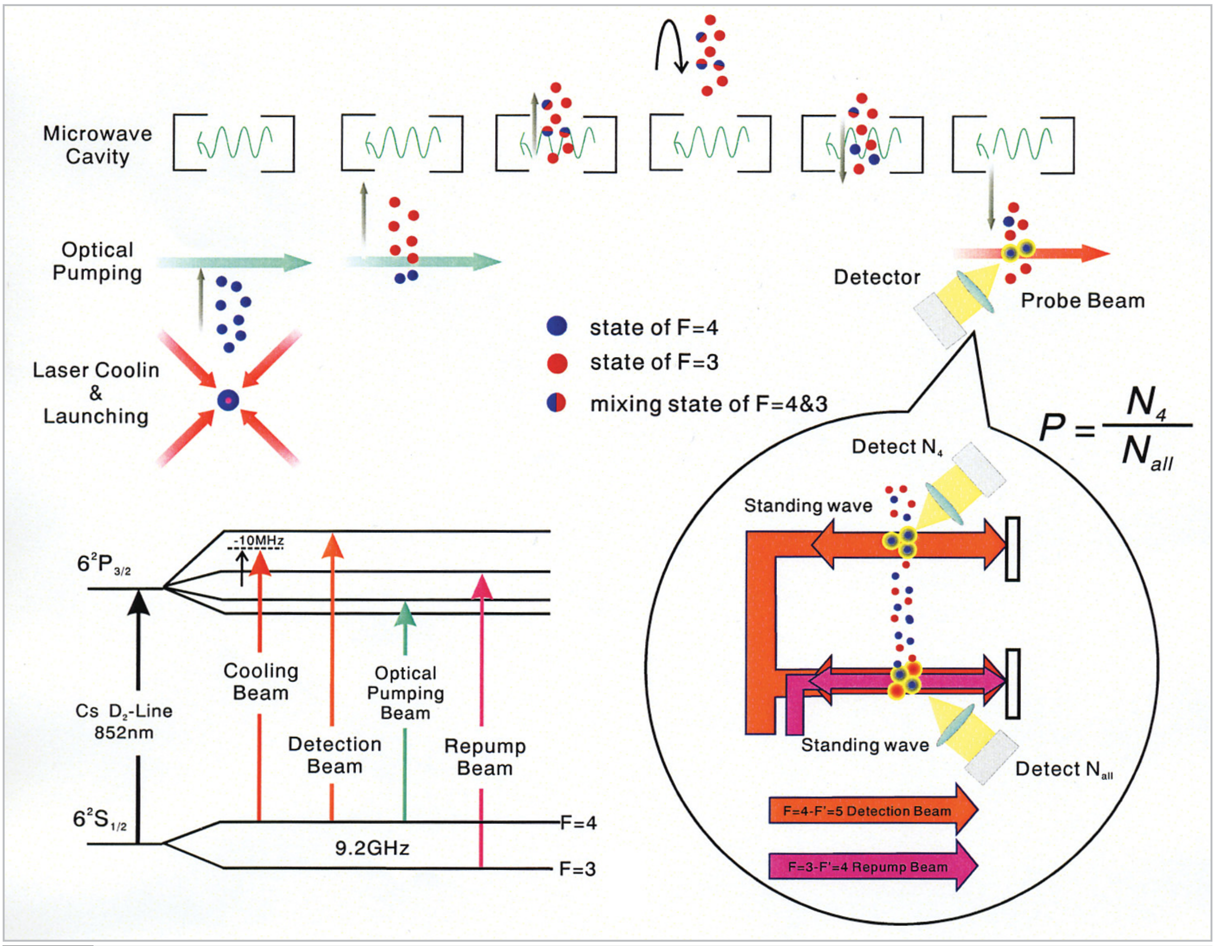

Fig.8 Schematic diagram of microwave interaction and signal observation (normalization)

tion to the F = 4 state. The number of these atoms is maximized when the microwave frequency coincides with the clock frequency of the cesium atom. The microwave frequency with this maximum of atoms in the F = 4 state will be 9,192,631,770 Hz, in accordance with the definition of a second, without taking frequency shifts into consideration.

Since the intensity of fluorescence is proportional to the number of atoms, if a probe beam resonant with the F = 4 state is inserted into the detection section and the intensity of fluorescence is observed, the number of atoms that moved to the F = 4 state can be determined. However, since the launching efficiency of the cold atoms is not constant, the absolute number of atoms that move to the F = 4 state may fluctuate. In order to eliminate the effect of this fluctuation, the number of all launched atoms (N_{all}) as well as the number of atoms in the F = 4 state (N_4) are observed at each launching, and the ratio of the atoms that transition to the F = 4 state to all launched atoms (N_4/N_{all}) is determined to normalize observed quantities.

The detection section has three view ports through which the laser beams irradiate the atoms. PDs are installed in two view ports, at top and at bottom, to observe fluorescence. The laser beam ($F = 4 \rightarrow F' = 3$) is inserted into the middle view port not equipped with a PD. The laser beam ($F = 4 \rightarrow F' = 5$) resonant with the atoms of the F = 4 state is inserted into the top port, and is reflected by a mirror to form a standing wave. In this port, the number of atoms (N_4) that have moved to the F = 4 state by the microwave is measured. In the bottom port, the number of all launched atoms (N_{all}) is measured. In this port, a standing wave of the $F = 3 \rightarrow F' = 4$ laser beam and the standing wave of the $F = 4 \rightarrow F' = 5$ laser beam are superposed. An atom of the F = 4 state caused to transition by the microwave will resonate with the $F = 4 \rightarrow F' = 5$ laser beam and emit fluorescence. Conversely, an atom of the F = 3 state not subject to transition by the microwave will resonate with a $F = 3 \rightarrow F' = 4$ laser beam, enter into the F = 4 state temporarily, and resonate with the $F = 4 \rightarrow F' = 5$ laser beam and emit fluorescence.

Thus, in the bottom port, the total number of launched atoms is observed at each launch. Both in the observation of N_4 and of N_{all}, a single laser beam ($F = 4 \rightarrow F' = 5$) is divided into two beams so that fluctuation of fluorescence due to frequency variation of the laser beam is eliminated. Part of the repump beam previously used for MOT is separated and employed for the laser beam used to observe atoms in the F = 3 state ($F = 3 \rightarrow F' = 4$).

Establishing the detection system, the interaction of cesium atoms with the microwave are allowed to be observed. Because the next ensemble of atoms cannot be launched before the previously launched atoms ensemble arrive at the detection section, a series of experimental launches, detection,

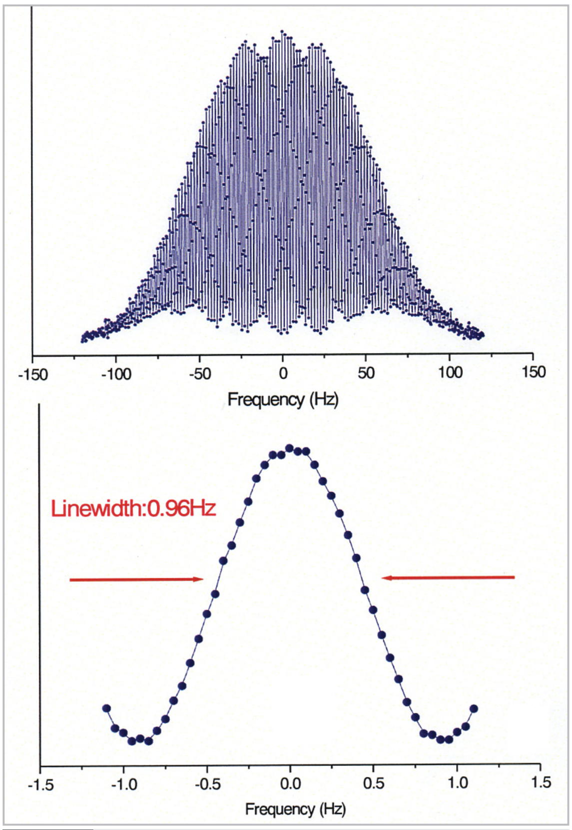

Fig.9 *Observed Ramsey fringe (general view and enlarged view of the core of the signal)*

(Upper figure) General view. (Lower figure) Enlarged view of core portion. Launching initial velocity: 4.4 m/s; launching height: 100 cm; drift time: 520 ms; obtained linewidth: 0.96 Hz and frequency change is repeated while the frequency is changed in a discrete manner, and the value of N_4 / N_{all} is plotted to determine the overall spectrum of the Ramsey fringe.

Fig.9 shows the obtained Ramsey fringe, reflecting the results when atoms were launched with a detuning of 5.2 MHz (initial velocity 4.4 m/s), with a theoretical drift time of 520 ms and a Ramsey fringe at 0.96 Hz. The observed Ramsey fringe was thus less than 1 Hz, representing the successful achievement of our initial target (to obtain a Ramsey fringe of less than 1 Hz).

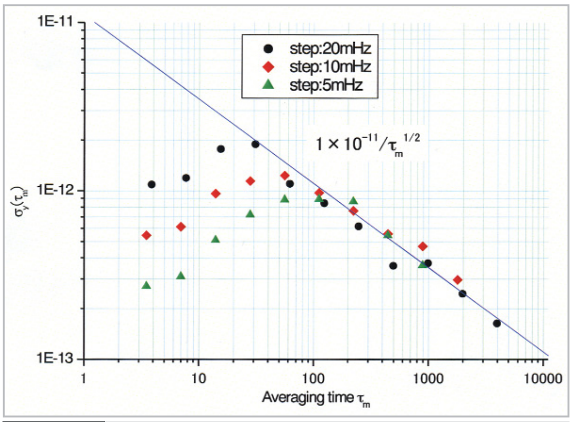

Fig.10 Frequency stability (Allan deviation diagram)

3.4 Frequency stabilization

Although the S/N ratio of the obtained Ramsey fringe was still inadequate to achieve accuracy of 10^{-15}, we evaluated frequency stabilization by locking the microwave frequency to the center of the Ramsey fringe in order to determine the current frequency stability. The method of frequency stabilization in this case is simple: all that is required is to compare signal intensities at the two microwave frequencies ($\nu_0-\Delta\nu/2$ and $\nu_0+\Delta\nu/2$) at which the intensity of the Ramsey fringe is half of the maximum value and to vary the center frequency of the microwave such that the signal intensities at these two frequencies become equal. Normally, variation in the center frequency of the microwave is determined as a function of the difference between the intensities. However, for the time being we have adopted a simpler method: the frequency of the microwave is changed stepwise by a constant amount in the direction in which the difference between the intensities at the two points decreases. The oscillating frequency of the microwave frequency-stabilized by this method was measured and determined to be approximately half a day; this frequency stability is expressed as an Allan standard deviation.

Fig.10 shows the obtained Allan deviation diagram. The vertical axis represents frequency stability $\sigma_y(\tau_m)$ and the horizontal axis represents averaging time τ_m. The figure shows the results for three different frequency increments: 5 mHz, 10 mHz, and 20 mHz.

Since at present the frequency variation is set to a given quantity, short-term stability (where averaging time is less than 100 sec) returns a value better than would be seen in actual practice, and hence this value is unreliable. However, a frequency stability with an averaging time of more than 100 sec results in a value that independent of the size of the frequency increment, and this value decays at a slope of $1/\tau_m^{1/2}$. Based on these results, it can be said that long-term stability values are realistically reflected under the present system. Accordingly, we determined that the frequency stability of the present atomic fountain was on the order of $1\times10^{-11}/\tau_m^{1/2}$, based on the determined long-term stability values.

Stability must be further improved in order to attain stability of a level of 10^{-15}. Since stability under the present system depends on the S/N ratio of the obtained Ramsey fringe, we expect that if the S/N ratio is further improved, the overall stability of the frequency standard will improve.

4 Future challenges

In accordance with our initial target, we have succeeded in obtaining a Ramsey fringe of less than 1 Hz, and in attaining a frequency stability in the frequency standard. However, as can be seen in formula (1), in order to attain stability of a level of $X\times10^{-15}$ (where X is a low number), a signal-to-noise ratio of approximately 1,000 is required. Since the currently observed S/N ratio is not even 50, improvement of the S/N ratio is presently a top priority.

Several methods of improving the S/N ratio may be proposed. Under one such method, the height of the launched atoms may be lowered to increase the number of atoms that fall into the detection section. As can be seen in Fig.7, if the launch height is increased, it will take longer for the atoms to reach the detection section, and the number of atoms detected at the detection section will decrease due to diffusion. However, if the time of flight of the atom is reduced, the extent of diffusion will decrease and the signal strength will increase.

Atoms must be launched to a height of about 30 cm in order to obtain a Ramsey fringe with a linewidth less than 1 Hz. That being said, the present CRL atomic fountain features a long distance from the trap section to the cavity (approximately 70 cm, as opposed to other atomic fountains worldwide, where this distance ranges from 30 to 40 cm); if this distance can be somewhat shortened, the atomic launch height may be able to be lowered, with a resultant increase in signal strength.

Moreover, we believe that signal strength may be increased by increasing the efficiency of the detection section. An atom emits fluorescence in all directions when it interacts with the probe beam. However, with the present structure, only fluorescence emitted toward a certain solid angle can be observed. Detection efficiency is optimistically estimated to be about 15%. Accordingly, it is believed that structural modification to permit efficient collection of fluorescence emitted in all directions will lead to increased signal strength. Such modifications would entail reconstruction of the entire device; minor modifications of the initial prototype will not solve the problem. Consequently we plan to incorporate these and other improvements in the manufacture of a second atomic fountain, after having thoroughly determined the weak points of the present fountain.

Development of the atomic fountain standard will not end with the observation of the Ramsey fringe. The center frequency of the observed Ramsey fringe must be measured and the deviation of the result from the defined value must be calculated. Several techniques are available to determine this center frequency; it will be necessary to determine by trial and error which one will provide the correct value most quickly, as well as to develop a corresponding algorithm.

Moreover, as can be seen in formula (1), even if a signal is obtained with an S/N ratio of approximately 1,000, a measurement time of approximately one day becomes necessary to achieve a frequency stability of 10^{-15}. The entire atomic fountain system must therefore remain stable for at least one day. Since the atomic fountain standard consists of a collection of component technologies (such as vacuum technology, laser optical technology, and microwave technology) we must pay greater attention to the relative stabilities of all component technologies.

Furthermore, as mentioned in Section **1.2** in this paper, we must evaluate all of the factors influencing frequency shift in the development of the primary frequency standard. The atomic fountain standard has the benefit of few shift factors relative to the atomic-beam frequency standard, while at the same time presenting the problem of calculation of collisional shift. Estimation of this collisional shift also represents a significant future challenge.

5 Summary

Development of an atomic fountain primary frequency standard was initiated at the CRL. With the goal of allowing practical use of the atomic fountain standard, we have manufactured a full-size atomic fountain device as a primary frequency standard. The device, consisting of a trap section, a detection section, and a microwave interaction section, was made mostly of non-magnetic materials, and high vacuum of the microwave interaction section was established as 3×10^{-10} torr. For laser cooling and atomic launching, we have established a high-power light source system based on semiconductor lasers. We have succeeded in cooling cesium atoms to below 2 μK by combining the MOT and PGC techniques and have launched the cooled atoms efficiently by combining the moving molasses and PGC methods. The atoms were then interacted twice with a microwave within the microwave cavity installed on the atomic path; this led to observance of a Ramsey fringe of less than 1 Hz. We succeeded in frequency-stabilizing the microwave to the center of the Ramsey fringe and attaining a stability on the order of $1 \times 10^{-11} \tau^{-1/2}$. In order to establish a frequency standard featuring accuracy of 10^{-15}, we must first address a number of future challenges: enhancement of the S/N ratio of the Ramsey fringe, improvement of the frequency stabilization system, and evaluation of factors influencing the frequency shift, among others.

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