3-5 Development of an Ultra-Narrow Line-Width Clock Laser

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An optical lattice clock and a single ion optical clock are being developed in National Institute of Information and Communications Technology (NICT). Diode lasers are used for the development of extremely narrow linewidth clock lasers for optical frequency standards. Using the Pound-Drever-Hall technique, the required reduction of linewidth was achieved by locking the laser to an ultrahigh-finesse ultralow-expansion glass (ULE) reference cavity, which is set in the high vacuum chamber with a constant temperature and isolated against environmental noise and vibration. As a result, the laser linewidth is decreased down to several Hz. The Allan deviation is less than 4×10^{-15} at an averaging time over 100 s. A vibration-insensitive optical cavity has been designed, aiming the linewidth below 1 Hz. In this chapter, we report the present status of development of the clock lasers at NICT.

Keywords
Laser frequency stabilization, Diode laser, Optical reference cavity, Optical clock, Optical frequency standard

1 Introduction

The second, the current time and frequency standard unit, is defined according to the hyperfine structure transition of cesium atoms by the General Conference of Weights and Measures in 1967 and its accuracy is reached to 4×10^{-16} recently[1]. However, it has become difficult to achieve a higher accuracy since the measuring time is long in order to reach this accuracy. Since the development of the coherent frequency comb generators using mode-locked femtosecond lasers[2][3], novel frequency standards based on narrow optical transition frequencies are being developed rapidly as a result of high optical oscillation frequency being capable of being measured at 4 – 5 digits or more than the oscillation frequency of the micro-wave range.

The development of an optical clock with an uncertainty of 10^{-17} or less is divided into two types. The first is the “optical lattice clock”[4][5], neutral atoms are trap in the optical lattice “magic wave length” and the second is the “single ion clock”[6], single ion is confined to the Lamb-Dick regime. The extremely narrow spectrum optical transitions are used in both optical clocks as clock transitions. National Institute of Information and Communications Technology (NICT) is currently developing “a strontium (Sr) optical lattice clock” and “a single calcium (Ca^+) ion optical clock”[7][8]. A $^1S_0$–$^3P_0$ spin forbidden transition (698 nm wavelength, 10 mHz natural linewidth) and A $^2S_{1/2}$–$^2D_{5/2}$ electric quadrupole transition (729 nm wavelength, 0.2 Hz natural linewidth) are used as clock transitions of Sr atoms and a single Ca^+ ion respectively. Extremely narrow linewidth and ultrastable clock lasers play a significant role in recent development of optical frequency standards, since the laser linewidth often limits the accuracy of frequency measurements.

The clock laser of the Sr optical lattice clock utilizes a diode laser. For spectroscopy of $^2S_{1/2}-^2D_{5/2}$ electric quadrupole transition in Ca^+ ions, a Ti:sapphire laser is a representative light source[9] until now. With the progress in quantum-well semi-conductor lasers in recent years, a diode laser of 730 nm can be manufactured. Since the saturated absorption power density is only 5×10^{-7} mW/cm^2 for Ca^+ ion, a low energy consumption, compact size and robust structure diode laser is used.

Research and development on the "Sr optical lattice clock" clock laser is detailed in a separate paper[10]. However, here we will explain the development of the "single Ca^+ ion optical clock" in detail.

2 Clock laser stabilization

2.1 The composition and control system for the clock laser

Figure 1 shows a schematic of the laser frequency stabilization. Up until now, we have assembled a Littman-Metcalf external cavity diode laser (ECDL) utilizing an antireflective (AR) coated laser diode (LD) (Toptical, 730 nm, 5mW or 10mW) and developed a clock laser[11]. However, in 2009, a single longitudinal mode laser diode (Opnext, HL7301MG) with a 730 nm band InGaAsP multi-quantum well structure, 75 mA low-current operation, 40 mW output is manufactured. We antireflective (AR) coated it (by Koshin Kogaku Co., Ltd.) and assembled it as a 5 mW output ECDL. In addition, as result of amplifying the output of the slave laser up to 40 mW by the injection locked method and cleaning the spatial mode using polarization-maintaining signal mode (PANDA) fiber, we obtained a maximum 12 mW TEM_{00} mode light at the exit end of the fiber. Using the Pound-Drever-Hall (PDH) method[12], we stabilize an extremely narrow linewidth clock laser. A weak laser light of 100 μW is phase modulated by an electro-optic modulator (EOM, Linos PM25) operating at 15

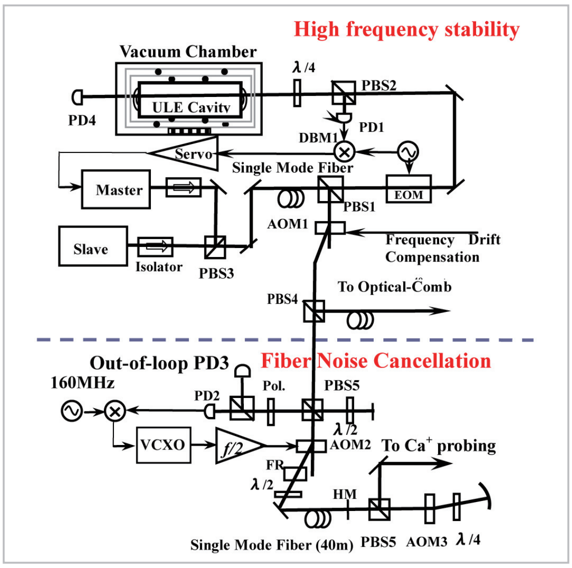

Fig.1 Experimental configuration of clock laser system

The paths of the laser beams and the electric signals are denoted by thick lines and thin lines, respectively. Acronyms are photodiode (PD), double-balanced mixer (DBM), polarization-beam splitter (PBS), electro-optic modulator (EOM), half wave plate (λ/2), quarter wave plate (λ/4), acousto-optic modulator (AOM), Polarizer (Pol.), Faraday Rotator (FR), and half Mirror (HM).

MHz, and it is coupled to TEM_{00} mode of the ultrahigh finesse ultralow expansion (ULE) glass reference cavity in the high vacuum chamber (10^{-7} Pa). The reflected light from the ULE reference cavity is detected by a Si PIN photodiode (PD1). After demodulation of photocurrent in a double-balanced mixer, the low-frequency component is amplified, integrated, and fed back to the master laser via two channels of the electrical servo circuit: a slow feedback loop (~100 Hz) – driving the PZT of the ECDL mirror – adjusts the laser frequency to reference cavity resonance frequency. Fast frequency fluctuations are compensated by superimposing the feedback current signal onto the laser cathode. The total servo bandwidth reaches to as large as 1 MHz. A portion of the stabilized laser beam is transmitted by a PANDA fiber of 10 m length to the optical comb that we developed[13] for measuring and evaluating the laser frequency. The remaining laser beam is transmitted to a separate room by a PANDA fiber of 40 m length, and is frequency shifted by an acousto-optic modulator (AOM), then it was used to observe quantum jumps of the trapped single Ca^+ ion.

2.2 The impact of environmental disturbance on the optical reference cavity and optical reference cavity control

Because the frequency of the clock laser is stabilized at the resonance frequency of the optical reference cavity, the frequency stability of the optical reference cavity is the most important factor.

The Fabry-Perot optical reference cavity consists of two mirrors that face each other with a spacer placed in between. When integral multiple of the beam's half wavelength is equal to cavity length, the frequency is the resonance frequency. Consequently, even a very small change in the cavity length can change the resonance frequency. The cavity length and resonance frequency changes are expressed in the Equation:

$$\Delta\nu / \nu_0 = \Delta L / L \tag{1}$$

where L is the optical path length, ΔL is the change in the optical path length, ν_0 is the resonance frequency and $\Delta\nu$ is the change in the resonance frequency. If the wavelength is 729 nm, the refraction index is 1 and the cavity length is 10 cm, the cavity frequency changes 4 Hz when the cavity length is changed by 1 fm. In other words, in order to achieve a 1 Hz linewidth, the optical reference cavity length must be controlled with an accuracy of less than 1 fm. Consequently, it is necessary to analyze and suppress the main factors that impact on the resonance frequency of the optical reference cavity and create a design of vibration insensitive optical reference cavity.

One of the factors is fluctuation of atmospheric pressure. The change in refractive index between the two mirrors results the change in optical path length when fluctuation of atmospheric pressure arises. In order to prevent this, it is necessary to insert the optical reference cavity into an ultrahigh vacuum to ensure that fluctuation of atmospheric pressure do not influence the optical reference cavity.

Next, changes in the cavity length caused by thermal expansion in the optical reference cavity must be considered. Changes in the cavity length due to temperature changes can be expressed by the Equation:

$$\Delta L = \alpha L \Delta T \tag{2}$$

where α is the thermal expansion coefficient and ΔT is the temperature change. The thermal expansion coefficient α should be small for the optical reference cavity materials. Sapphire is one of these materials. The temperature of the sapphire is 3 – 4K and α is extremely small at 10^{-11} K^{-1}. However, it is not easy to cool the optical reference cavity to liquid helium temperature. The ULE glass manufactured by Corning and Zerodur manufactured by Schott are considered to be other alternatives. Although these α are 10^{-8} K^{-1}, they have large differences that are the phenomena known as creep or ageing drift. Creep refers to the very slow change in the glass crystal structure with time. The ULE change is one digit smaller than Zerodur. Furthermore, ULE smoothly changes but Zerodur repeats non-continuous changes to change shape[14]-[16]. ULE glass is often selected for materials of optical cavities. Since the S_iO_2 base of ULE glass is doped with T_iO_2, the polarity of thermal expansion coefficient can be reversed at room temperature by the doping amount and homogenization. As a result, if the zero-crossing temperature is found and the ULE glass is kept to this temperature, a thermal expansion coefficient less than 10^{-10} K^{-1} in substance is possible. However, even if the ULE glass is maintained to a temperature close to zero-crossing and α becomes 1×10^{-10} K^{-1}, and if the temperature of the 10 cm optical reference cavity changes 1 mK, it is apparent from Equations (1) and (2) that the cavity frequency drifts 40 to 50 Hz. Regardless of this, it is very difficult to control the temperature change under 1 mK in actual practice.

As it happens, as stated above, the optical reference cavity is contained in a vacuum chamber. In such case, if the temperature changes inside and outside the vacuum are respectively ΔT_{out} and ΔT_{in}, the ratio of both will have the following relationship[14]:

$$\Delta T_{in} / \Delta T_{out} = 1 / (f\tau) \tag{3}$$

where f is the frequency of temperature change and τ is thermal time constant. The lower the thermal conduction, the larger τ becomes. If f is 0.1 Hz and τ is 24 hours, then $\Delta T_{in}/\Delta T_{out}$ becomes approximately 10^{-4}. The frequency drift of the optical cavity inside the vacuum chamber is significantly reduced, which is caused by the temperature change outside the vacuum chamber.

Furthermore, environmental noise sources that modulate the optical reference cavity length are mainly of acoustic origin in the range above 50 Hz and seismic origin from 1–50 Hz. In particular, the vibrational noise of low frequency range (0.1 – 100 Hz) largely affects the laser linewidth. To isolate vibration noise in a low frequency range, it is necessary to lower the resonance frequency of the optical platform that holds the optical reference cavity as much as possible. In 1999, the optical cavity had been protected from vibrational noise by mounting the vacuum chamber on a passively isolated optical platform. The optical platform is suspended by vertical strands of surgical tubing stretched to 3 m (approximately pendulum mode frequency of 0.3 Hz) and stabilized the laser with a sub Hz linewidth[17]. Recently, Minus-K (Minus K Technology: Isolation from 0.5 Hz) passive vibration isolated optical platform and an active vibration isolated optical platform (Table Stable) have been put on the market. These platforms have proven to be very effective for stabilizing laser frequency.

We choose a high finesse ULE (space and substrate of mirrors) reference cavity (Advanced Thin Films) whose free spectral range is 1.5 GHz. In the cavity, a photon lifetime of 33 μs is measured by the cavity-ring-down spectroscopy of heterodyne detection in cavity reflection. We estimate the finesse of the cavity as 156, 000. To reduce acoustic, thermal, and mechanical perturbation, the ULE optical reference cavity is inserted into a vacuum chamber, which is pumped by an ion pump to maintain the pressure at 10^{-6} Pa. Between the ULE reference cavity and vacuum chamber, two gold-coated oxygen-free copper cylindrical cans (high reflectivity for thermal radiation at room temperature) are placed. Two pairs of Viton O-rings are used for the thermal isolation between the ULE reference cavity and the inner can, and between the inner and outer cans. To minimize the long-term drift of cavity resonance, it is necessary to determine the temperature at which the coefficient of thermal expansion of ULE reference cavity becomes zero. It means that we need to control the ULE reference cavity in a wide range of temperature. By controlling six Peltier elements, two-stage active temperature stabilization is performed to prevent dew condensation on the windows at low temperature. Two small Peltier elements (series connection, keeping a balance of the cavity) are glued between the bottom of the outer can and the vacuum chamber. Other four Peltier elements are set in the bottom of the vacuum chamber. The external can is active-controlled at a lower temperature (the control current less than 1 A), and the vacuum chamber is maintained at room temperature of 23°C. The temperature fluctuation of the vacuum chamber is reduced to less than 10 mK. The vacuum chamber is isolated from environmental noise sources using a passively isolated platform with a resonant frequency of 0.5 Hz (Nano-k BM-4) and an acoustic proofing box.

2.3 Experimental results of the laser frequency stabilization

We stabilized the frequency of another clock laser (clock laser 2) to a ULE reference cavity (finesse of ~ 400,000, free spectral range ~1 GHz) using the method explained in **2.1**. For an evaluation of the linewidth of the laser,

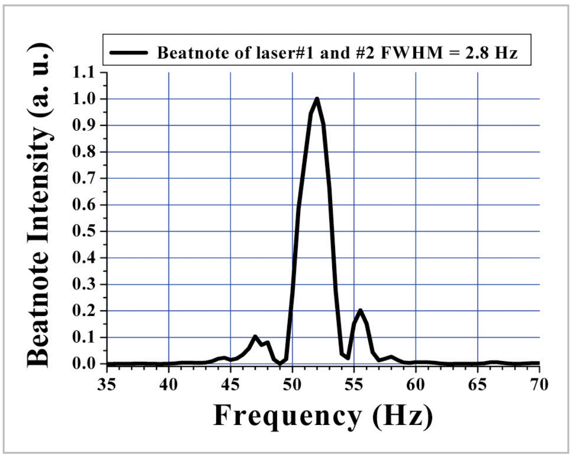

Fig.2 *Spectrum of heterodyne beatnote between two laser beams stabilized to two independent ULE reference cavities*

Acquisition time is 1 s. The resolution bandwidth of the spectrum analyzer is 1 Hz. The heterodyne beatnote linewidth is 2.8 Hz, The frequency axis is centered at a difference frequency of 795 MHz.

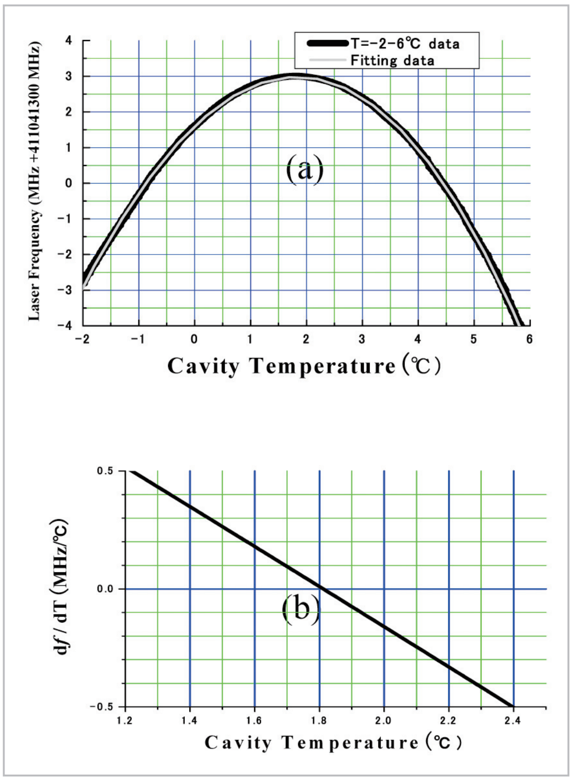

Fig.3 *Measurement of absolute frequency dependence on cavity temperature swept from −3°C to 6°C*

(a) shows the dependence with the laser frequency. The frequency axis is centered at a difference frequency of 411041300 MHz.
(b) shows a differential of resonance frequency obtained by a cubic polynomial of the fitting curve.

we measured the heterodyne beatnote between two narrow linewidth lasers individually stabilized to two ULE reference cavity systems, placed on two separate Minus-K platforms. Figure 2 shows a beatnote signal of the stabilized lasers, which is measured by a spectrum analyzer with a resolution bandwidth of 1 Hz and acquisition time of 1 s. The center frequency was 795 MHz and the beatnote linewidth is 2.8 Hz.

To minimize the long-term drift of cavity resonance, it is necessary to determine the zero-crossing temperature of the ULE reference cavity. We increase the temperature of the ULE reference cavity from −3°C to room temperature and simultaneously measured changes in the resonance frequency of this laser with the reference cavity (at 729.349 nm) by the femtosecond laser frequency comb, whose repetition frequency and offset frequency are linked to a 10 MHz radio-frequency supplied by a hydrogen maser standard. Figure 3(a) shows a measured absolute frequency depending on cavity temperature. The zero-crossing temperature of ULE reference cavity is around 1.8°C. This curve is fitted finely by a cubic polynomial, shown by a gray line in Fig. 3(a). The curve is differentiated and the result with a narrow range of 1°C ~ 2°C is shown in Fig. 3(b). From the differential line, we found that even a deviation of 0.1°C from zero-crossing temperature, the frequency drift will become 100 Hz / mK from zero. We need to determine zero-crossing temperature more precisely than this one-way temperature varying measurement. We carried out a temperature-fixed measurement of resonance frequency at different temperatures of 1°C ~ 2°C many times. Figure 4 shows the measured results, which are obtained over two months. The curve shown in the Fig. 4 is not as smooth as the curve shown in Fig. 3(a), which is considered to be caused by an ageing drift of the ULE cavity (~ a few kHz / day), because it takes several days to set and keep the ULE cavity at each precise tempera-

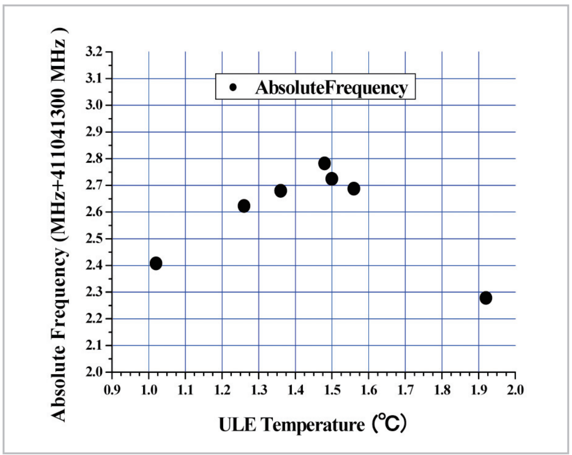

Fig.4 *Precise measurement of absolute frequency dependence on the cavity temperature*

The temperature range swept from 1°C to 2°C. The absolute frequency axis is centered at a difference frequency of 411041300 MHz.

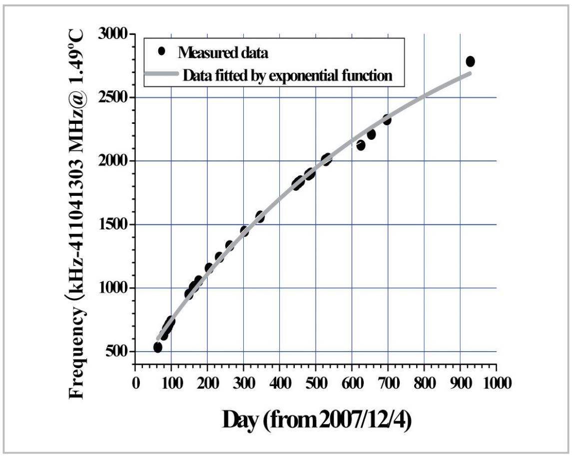

Fig.6 *Ageing drift of the ULE cavity*

The cavity is kept at 1.50±0.02°C over two years. The clock laser is locked to the cavity and the resonance frequency is measured by a femtosecond laser frequency comb. The data are fitted by an exponential function.

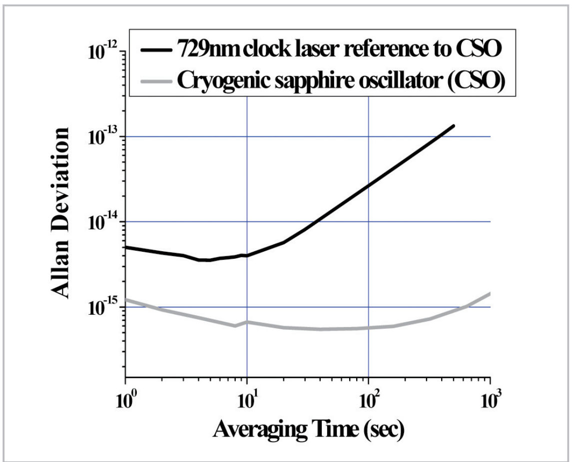

Fig.5 *Measured frequency stability of diode laser system (Black line) and 1GHz signal based on a cryogenic sapphire oscillator used as a frequency reference for the femtosecond laser frequency comb (gray line)*

ture. The zero-crossing temperature is around 1.49°C. Figure 5 shows measured frequency instability of the laser around this temperature. The Allan deviation is less than 5×10^{-15} at averaging time of 1 s ~ 10 s. A cryogenic sapphire oscillator (CSO) is used as a frequency reference for optical frequency comb[18]. The ageing drift of the ULE cavity is observed by measuring the resonance frequency of the laser, keeping the cavity at a regular temperature (1.49°C). Figure 6 shows the result. The measurement is gone on over two years. The ageing drift is decreasing with an exponential function. At first, long-term frequency drift is 5 ~ 6 kHz/day, now a typical long-term frequency drift is 2 ~ 3 kHz/day. A 0.03 Hz / s linear drift is measured.

3 Long-term frequency drift compensation

As discussed in **2.2**, even if the optical reference cavity temperature is precisely controlled, the resonance frequency will drift, because the optical reference cavity length has a change with aging. We compensate a long-term optical frequency drift of the clock laser for detecting the clock transition of Ca^+ ions more accurately.

Figure 7 shows the frequency drift compensation. The accusto-optic modulator AOM 1 (see Fig. 1 and Fig. 7) plays the role of a frequency compensation device. An approximately 80 MHz signal is generated by a deference frequency signal from the approximately 21 MHz signal, output from the AD9858 direct digital synthesizer (DDS) and the 101 MHz signal, output from the signal generator (Synthesizer 2). Then the signal power is amplified

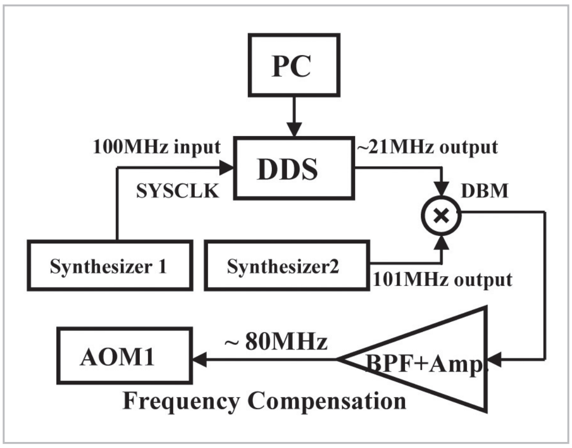

Fig.7 *Experimental configuration for laser frequency compensation*

Acronyms are personal computer (PC), direct digital synthesizer (DDS), band-pass filter (BPF), signal amplifier (Amp.) and acousto-optic modulator (AOM).

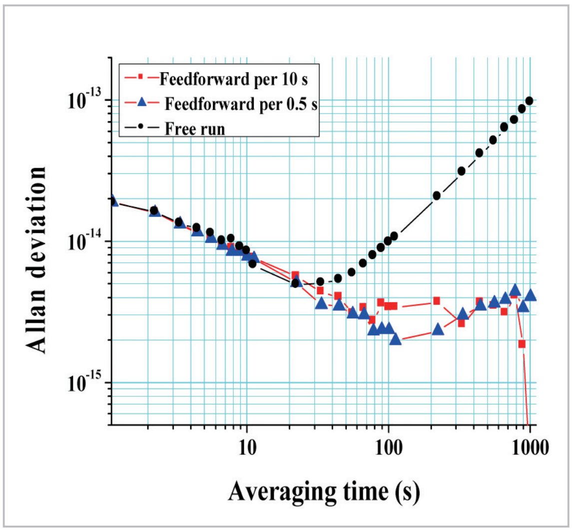

Fig.8 *Allan deviation of the clock laser*

Circle dot: values of the laser stabilized to ULE optical cavity without frequency compensation; square dot: values with compensation every 10 sec.; triangular dot: values with compensation every 0.5 sec.

and it drives the frequency shifter AOM1. The laser frequency is shifted when the clock laser passes AOM 1. Frequency drift be compensated by changing AOM 1 frequency, namely, subtracting the drift frequency measured by the optical frequency comb from the 21 MHz DDS output frequency using a computer for each period. A 100 MHz signal output from the signal generator (Synthesizer 1) is used as the reference clock signal of DDS, the frequency resolution of the DDS is 0.023 Hz at this case. Both synthesizers are linked to the 10 MHz radio-frequency supplied by the hydrogen maser standard.

Figure 8 shows frequency compensated results. Using the optical frequency comb referenced to the 1 GHz signal supplied by the CSO, the clock laser frequency stabilized in the ULE cavity is measured for 2,000 seconds and the average drift rate is calculated. The drift rate is + 0.0519 Hz/s. In Fig. 8, the circle is the Allan deviation data for the clock laser without frequency compensation and the triangle is the data when the frequency drift is compensated in a 0.5 second period. Since the DDS resolution is 0.023 Hz, – 0.023 and – 0.046 Hz is used as the appropriate ratio for the compensated quantity every 0.5 seconds in contrast to the drift rate of + 0.0519 Hz/s . The square is the Allan deviation when the frequency drift is compensated in a 10 second period using the same method. This figure shows that the frequency drift of the clock laser has been compensated. The Allan deviation from 50 seconds was less than $3 \sim 4 \times 10^{-15}$.

4 Precise cancellation of fiber-optical phase noise

To observe the clock transition, the clock laser light is transmitted to Ca^+ ion vacuum chamber through a PANDA fiber of 40 m length. However, optical phase in the fiber is extremely sensitive to mechanical and thermal perturbations. Phase noise modulation is induced by change of the optical path length of the transition fiber. It leads to a broadening of the optical field spectrum. To distribute the same optical frequency, we must cancel the phase noise. The cancellation scheme of the phase noise is also shown in Fig. 1. The laser beam is divided into two parts by the PBS5. A weak part of the laser beam (beam 1) is reflected to photodiode (PD2) by a mirror directly. Other strong part is frequency shifted by a frequency shifter (AOM2) of 80 MHz and is transmitted through a PANDA fiber of 40 m length. Then a half of the laser beam is returned to AOM2 by a half mirror and is frequency shifted again. A heterodyne beat signal ~160 MHz between the beam 1 and the round trip optical beam is detected by the PD2. It is mixed by a double-balanced mixer with a local reference of 160 MHz produced by a low noise frequency synthesizer (Rohde&Schwarz SM01, reference to H maser). The double-pass optical phase noise of the fiber link is revealed. In order to compensate the phase of the link, the double-pass optical phase noise is amplified and feedback to a voltage controlled crystal oscillator (VCXO) of 160 MHz. The output frequency signal of the VCXO is divided by 2, and then the power is amplified and drive the frequency shifter AOM2. The phase-noise is cancelled precisely.

For the evaluation of the performance of phase noise cancellation, we measured an out-of-loop heterodyne beatnote signal (from PD3, shown in Fig. 1) between the laser beam in front of AOM2 and the round-trip optical beam from the optical fiber. The experimental result is shown in Fig. 9. In Fig. 9(a), the grey line is a free-run optical field spectrum and the black line is a phase noise compensated spectrum with a center frequency of 160 MHz. Figure 9(b) shows the compensated spectrum with a magnified horizontal scale. The −3dB full linewidth (FWHM) of the beat-note signal is 1 Hz, limited by the resolution of the spectrum analyzer (1 Hz, Hewlett Packard 8560E). The result shows that the optical phase noise is canceled accurately after clock laser transmitting the PANDA optical fiber of 40 m length. In Fig. 9(a), the servo bandwidth of the phase-locked loop is 2 kHz.

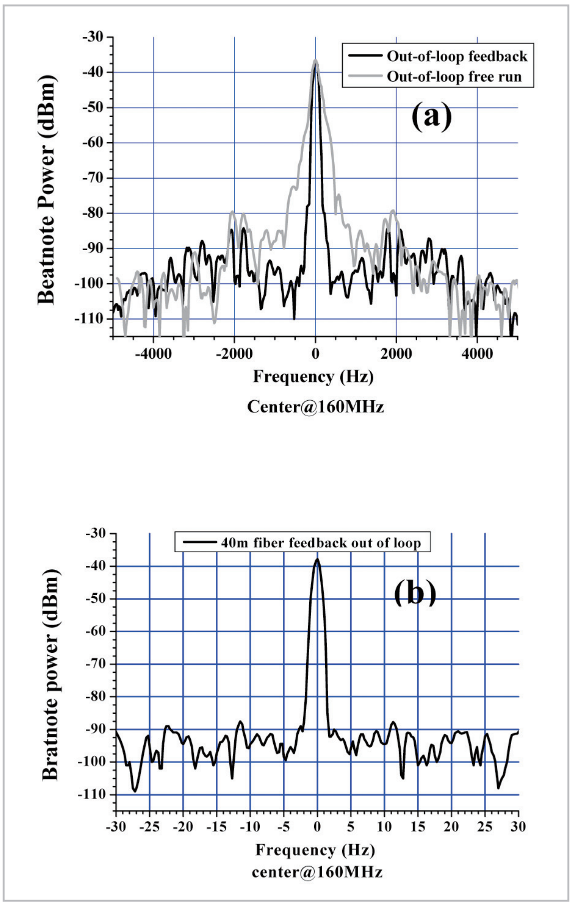

Fig.9 Heterodyne beatnote signal of out of loop

(a): The center frequency is 160 MHz and the bandwidth of the phase-lock loop is 2 kHz.
(b): The figure shows that the −3dB full linewidth of the beatnote is 1 Hz, limited by the resolution of spectrum analyzer.

5 A vibration-insensitive optical reference cavity design

As stated above, we have developed an ultra-narrow linewidth and an ultra-low frequency drift clock laser. A Minus-K vibration isolation platform and an acoustic insulated box are used to reduce the environmental disturbances on the optical reference cavity. As shown in Fig. 2 and Fig. 5, the results of the experiment show that the linewidth is still wider than 1 Hz and that the Allan deviation is 5×10^{-15} or more at 1 second for the short-term stability. As discussed in **2.3**, the finesse (400,000) for clock laser 2 is higher than that (156,000) of clock laser 1. However, the short-term stability for clock laser 2 measured by the optical comb is the same level as clock laser 1. In addition, the short-term stability value measured at night is better that the value measured during the day for both. It is considered that these results are caused by the vibration disturbance exerting on the optical reference cavity. In order to reduce this impact, one approach is designing a vibration-insensitive optical reference cavity. It means that the central distance between two mirrors of the optical reference cavity does not change when vibration disturbance is applied. Several studies have already been reported[19]–[22].

Vibration-induced elastic deformation depends on the material, geometry and mounting configuration of the optical reference cavity. It can be quantitatively analyzed by finite-element analysis method. Using this method, minimal deformation is calculated by optimizing geometry and mounting configurations of the optical reference cavity. Vibration-insensitive optical reference cavity is designed.

Vibration-insensitive optical reference cavities are usually divided in to vertical and horizontal cavities. Since horizontal optical reference cavities are easy to install, we selected a ULE cut-out cavity similar to that shown in Fig. 10[22]. Using finite-element analysis method, we calculate the minimal displacement of the cavity mirror by modifying the cut-out positions (X1 and X2 in the Figure) and mounting points based on a 10 cm diameter and 10 cm long ULE cut-out cavity. The result is that the mirror displacement is the smallest when the cut-out positions are X1 = 7.7 mm and X2 = 44 mm and the mounting positions are 10.9 mm and 46.5 mm away from the cavity end section and the vertical axis of the cross section. The vertical axis in Fig. 11 shows the displacement of one mirror along the optical axis of cavity (ΔL, unit is mm) when a 9.8 m/s^2 acceleration (gravity acceleration 1 G) is applied in a vertical direction. The horizontal axis shows the position of 1 mm up and down from the center of one of the mirrors (the center position shown by 1 in Fig. 11). The displacement of the center of the mirror is 1.3 × 10^{-13} m along the direction of the optical axis. A change of the length of the optical cavity is 2.6 × 10^{-13} m. The machining error for the cavity produced by ATF is ± 0.25 mm and the result of the simulation including this machining error is ~ 1 × 10^{-12} m.

We measured the acceleration on the Minus-K using an accelerometer. The acceleration of the 0.5 Hz resonant frequency of the Minus-K platform is several μG in the laboratory condition. Equation (1) shows that the resonance frequency variation ($\Delta\nu$) with the mirror displacement is less than 0.1 Hz. This satisfies the condition for a clock laser of the Ca^+ ion optical frequency standard. We plan to develop sub-Hz linewidth 729 nm clock laser utilizing this ULE optical reference cavity.

Furthermore, if an even narrower linewidth

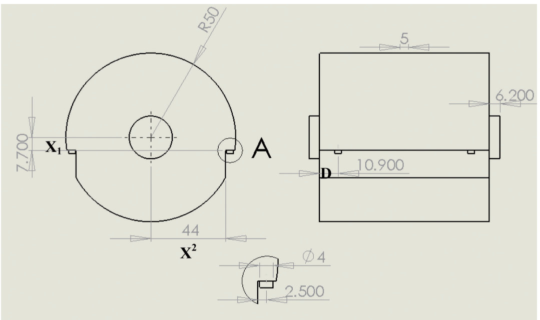

Fig.10 *Cut-out cavity*

Cut-out position from the center: X1 = 7.7 mm; X2 = 44 mm. Support pad: Φ 4 mm Viton rubber. The center of the 4 pads is separated from two end sides of the optical cavity by D = 10.9 mm and 46.5 mm from the vertical axis of the cross section.

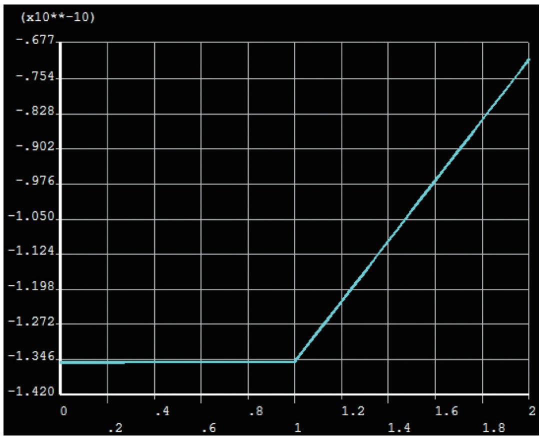

Fig.11 *Simulation results for mirror displacement*

This shows displacement ΔL near the mirror center when 1 G gravitation is applied to the optical cavity in the vertical direction. Position 1 is the center of mirror, 0 is 1 mm below the center, 2 is 1 mm above. Vertical axis: displacement of the one-sided mirror (mm).

clock laser is developed, there will be a problem with not only external environmental noise but also thermal noise caused by the mirrors and spacers connecting with the finite heat bath. To reduce this thermal noise, we can either reduce the temperature or raise a mechanical Q factor of the oscillator using materials such as fused silica[23]. Furthermore, if the optical reference cavity length is longer due to Equation (1), the resonance frequency variation ($\Delta\nu$) will become smaller. Consequently, our group has designed a 30 cm optical reference cavity[24].

6 Conclusion

We have developed an ultra-narrow linewidth clock laser that is key element in optical frequency standard. This clock laser has a linewidth of 2 Hz and an Allan deviation value which evaluates the stability of less than 5×10^{-15} for 1 – 10 seconds. The long-term frequency drift is 0.03 Hz/s when the clock laser is maintained at zero-crossing temperature. We have compensated the long-term frequency drift using an acousto-optical device and Allan deviation value is reduced to 3×10^{-15} for 1,000 seconds.

Since the clock transitions selected for the Sr optical lattice clock and the single Ca^+ optical clock have both the linewidths far narrower than 1 Hz, we will put all our efforts into research in the aim of further narrowing the linewidth of the clock laser by one digit.

We would sincerely like to thank Dr. Yang Tao (Beijing Jiaotong University) for simulating the cut-out optical reference cavity using the finite-element analysis method.

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