A Clock Laser with High Frequency Stability and Highly Precise Transfer

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1. INTRODUCTION

An optical frequency standard of a single Ca^{+} ion trap is being developed in NICT. At the 18th meeting of the CCTF in June 2009, the $^2S_{1/2}$-$^2D_{5/2}$ electric quadrupole transition of the $^{40}Ca^{+}$ was included in the list of recommended frequencies. This transition wavelength is 729 nm and natural linewidth is 0.14 Hz. It means an extremely stable clock laser is necessary to make good use of narrow linewidth.

For spectroscopy of the $^2S_{1/2}$–$^2D_{5/2}$ electric quadrupole transition in Ca^{+} ions, a Ti:Sapphire laser is a representative light source. Ti:Sapphire lasers offer high output power and good tenability. An additional electro-optic modulator (EOM) is easy to be inserted into their open geometries for high frequency feedback. A highly stabilized Ti:Sapphire laser with linewidth of 50 Hz has also been reported [1].

While Ti:Sapphire laser has a big size, high energy consumption, the whole system based on them may be relatively complicated and difficult to maintain. Inexpensive and nearly maintenance-free diode laser light source is always attractive. We introduce a 729nm diode laser light source. In this article, we describe the development of the 729 nm diode laser as a clock laser. This clock laser light is transmitted to probe quadrupole transition of the $^{40}Ca^{+}$ by a polarization-maintaining single-mode optical fiber of 40 m length. Phase noise modulation is induced by change of the optical path length of the transmission fiber. We also describe a cancellation method of fiber-optical phase noise. Employing this clock laser, we have observed the quantum transition spectra of a laser-cooled single $^{40}Ca^{+}$ ion on the basis of $^2S_{1/2}$–$^2D_{5/2}$ electric quadrupole transition. On the other hand, this clock laser frequency has also been locked to this transition frequency of the $^{40}Ca^{+}$.

2. EXPERIMENTAL PROCEDURE

2.1. Stabilization of Laser Frequency

We try to stabilize 10 mW, antireflective coated laser diode with a center wavelength at 730 nm (Sacher lasertechnik, SAL-730-10) as a clock laser. To obtain a spectrally single-mode emission and to reduce linewidth, we placed the solitary laser in an extended cavity with the Littman-Metcalf configuration. This extended cavity diode laser (ECDL, called master laser) output power is 4.7 mW at 729 nm with an injection current of 110 mA. We know that the mode qualities of diode lasers are different in different frequency regions. In this laser, two orthogonal polarization modes are emitted simultaneously even in the ECDL configuration. We filtered out one polarization mode with a lower power using an optical isolator with a 60 dB isolation ratio (Linos DLI 3). The obtained pure single-mode output power is 3 mW. The other diode laser (injection laser) is injected by the master laser to attain a high output power of 18mW.

Because the linewidth of the $^2S_{1/2}$–$^2D_{5/2}$ electric quadrupole transition is only 0.14 Hz, an extremely narrow linewidth clock laser is essential. To compress the spectral linewidth and frequency drift of the laser, the master laser is actively stabilized to a Fabry-Perot reference cavity made from ULE material (spacer and substrate of mirrors) by employing the Pound-Drever-Hall technique. We choose a very high finesse ULE (for all parts) reference cavity (Research Electro-Optics) 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 156000.

The optical stabilization scheme is shown in Fig. 1. A part of the injection laser light is coupled to a polarization-maintaining single-mode fiber to obtain a single spatial TEM_{00} mode. A $\lambda/2$ wave plate is inserted in the optical path before the fiber so that we can make the perfect matching of polarization between the laser beam and the fiber. This matching reduces the polarization modulation of the fiber greatly. Using an EOM (Linos PM 25), weak FM sidebands at 15 MHz with a power ~ 1% of that of the carrier are generated. The Brewster angled windows of the EOM keep the direction of laser polarization identical to that of the electric field on the crystal so that the residual amplitude modulation is reduced. A weak beam intensity of 100 μW is coupled to the ULE reference cavity to reduce the cavity resonance frequency drift owing to mirror deformation by the power absorption. The reflected light from the cavity is separated from the incoming light using a λ/4 wave plate in combination with a polarizing beam splitter and 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.

2.2. Minimization of Long-Term Frequency Drift and Environmental Noise Sources

For the construction of an extremely stable laser, it is very important to minimize a long-term frequency drift and isolate the ULE reference cavity against acoustic, thermal, and mechanical disturbance, since a drift of the length of the ULE reference cavity would increase a frequency fluctuation in the measurement of the center frequency of the transition spectrum. Environmental noise sources, which are mainly of acoustic origin in the range above 50 Hz and of seismic origin from 1 Hz to 50 Hz, change the cavity length. Here, we introduce a system in the laser very successfully. To reduce the disturbance, the ULE reference cavity is placed in a vacuum chamber (see Fig. 1), air is pumped out by an ion pump to maintain the pressure at 10^{-6} Pa. Between the ULE reference cavity and the inner wall of vacuum chamber, two gold-coated copper cylindrical cans (high reflectivity for thermal radiation at room temperature) are placed. Two pairs of Viton O-rings are used for the support and 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 temperature of the ULE reference cavity in a wide range of temperatures. By controlling six Peltier elements, two-stage active temperature stabilization is performed to prevent dew condensation on the windows at low temperatures. Two small Peltier elements (series connection, keeping a balance of the cavity) are glued between the bottom of the outer copper 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

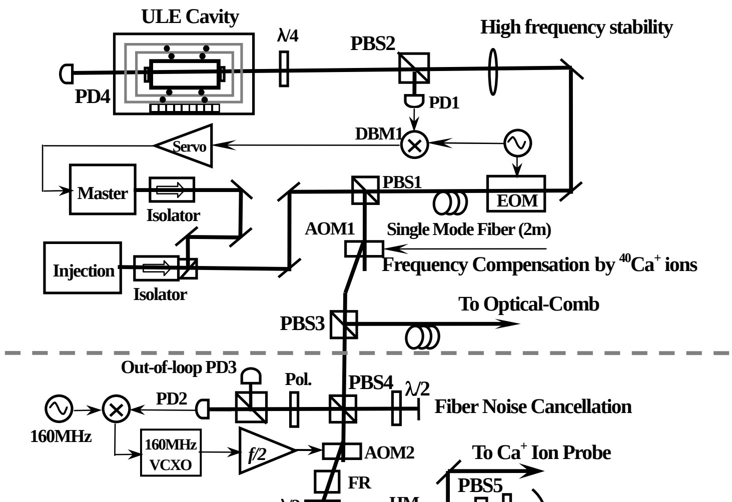

Fig.1. Experimental configuration of clock laser system: The paths of the laser beams and the electric signals are denoted by thick lines and thin lines, respectively. Acronyms are photodiode (PD), double-balanced mixer (DBM), polarization-beam splitter (PBS), electro-optic modulator (EOM), half wave plate (λ/2), quarter wave plate (λ/4), acousto-optic modulator (AOM), Polarizer (Pol.), Faraday Rotator (FR), and half Mirror (HM) .

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. 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 polarization-maintaining single-mode optical 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 transmission 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 PBS4. 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 an acousto optic modulator (AOM2) of ~80 MHz and is transmitted through a polarization-maintaining single-mode optical fiber of 40 m. 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 round trip optical phase noise of the fiber link is revealed. In order to compensate the phase shift caused by the link, the round trip optical phase noise is amplified and feedback to a voltage controlled crystal oscillator (VCXO) of 160 MHz. The output frequency of the VCXO is divided by 2, then the power is amplified and drive the frequency shifter AOM2.The phase noise is cancelled precisely. The servo bandwidth is 2 kHz.

2.4. Clock Laser Frequency Locked to a Single Trapped $^{40}Ca^+$ Ion

Employing this clock laser, we have developed a frequency standard based on a quadrupole transition between the $4^2S_{1/2}$ - $3^2D_{5/2}$ of a single $^{40}Ca^+$ ion. Its absolute transition frequency is measured as 411 042 129 776 395 (4.8) Hz [2]. Using an optical comb [3], we can compare this transition frequency with other optical frequency or rf frequency by lock the optical comb to this clock laser. We need to lock the frequency of the clock laser to the quadrupole transition frequency of a single $^{40}Ca^+$ ion. The frequency drift of the clock laser is existent due to long term ageing drift of the length of the ULE cavity and a fluctuation of temperature [4]. The frequency lock scheme is shown in Fig. 2.

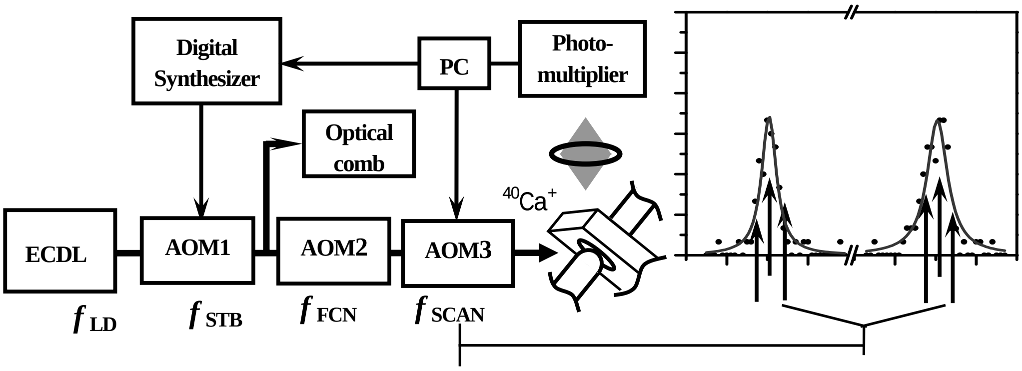

Fig. 2 A schematic of steering the laser frequency using the $^{40}Ca^+$ clock transition. AOM3 modulates the laser frequency to observe the excitation probabilities at six frequencies. PC: personal computer; FNC: fiber noise canceling (see Fig. 1).

The first, a single $^{40}Ca^+$ ion is trapped by a small radio-frequency Paul trap and is laser cooled using 397nm and 866nm lasers. The electron shelving technique [5] is used to detect the $4^2S_{1/2}$ - $3^2D_{5/2}$ transitions. When the $^{40}Ca^+$ ion absorbs a single 729 nm photon and is shelved in the $3^2D_{5/2}$ state, fluorescence on the cooling ceases until the ion is stimulated back to the ground state. By stepping the frequency of the 729 nm clock laser (with an AOM3) and counting the number of clock transition jumps over a given number of the clock laser pulse irradiation (duration 4ms). The spectra of the $4^2S_{1/2}$ - $3^2D_{5/2}$ transition can be measured. A stable dc magnetic field around 80μT is applied so that the clock transition line splits into ten Zeeman components. The absolute transition frequency is estimated as the average of the two inner ($m_{j'}$, $m_{j''}$) = (-1/2, -1/2) and ($m_{j'}$, $m_{j''}$) = (1/2, 1/2) Zeeman components, which is insensitive to the magnetic fluctuations. A sample of the spectra is shown in the right side of the Fig.2.

For the clock laser frequency lock, an AOM1 (80 MHz) is employed as a frequency compensator and the transition frequency is measured by the optical comb behind the AOM1. The AOM3 (350 MHz) is employed to scan optical frequency for measurements of clock transition. The absolute transition frequency is a sum of clock laser frequency (f_{LD}), the AOM1 frequency (f_{STB}), the AOM2 frequency (f_{FCN}, mentioned by § 2.3) and the AOM3 (f_{SCAN}) center frequency fixed to the center of the two inner Zeeman components. The AOM2 frequency is constant. At figure 2, for each lock cycle, scanning the AOM3 frequency, the excitation probability at six clock laser frequencies are measured at the suspected peak frequencies of two inner Zeeman components and both upper and lower half-width frequencies. Zeeman component, due to the combined effects of the true line-shape and the line-shape of the probing laser, is Lorentzian. Two true peak frequencies are calculated and the transition frequency is decided [6]. Comparing this transition frequency with the center of the suspected peak frequencies, a small offset frequency is produced, when the clock laser frequency shifts. This offset frequency is compensated to the AOM1. The transition frequency measured by the optical comb, keeps a constant value. The clock laser frequency is locked to a single trapped $^{40}Ca^+$ ion.

3. RESULTS

3.1 Laser Frequency Stability

Another narrow linewidth laser, based on the same 10 mW, AR coated laser diode had been stabilized to a ULE reference cavity (finesses of ~ 400000, free spectral range ~ 1.5 GHz) by a similar method. For an evaluation of the linewidth of the lasers, we measured the heterodyne beatnote between two narrow linewidth lasers, individually stabilized to two ULE reference cavity systems, placed on two separate Nano-K platforms. Figure 3 shows a beatnote signal of the stabilized lasers, which is measured by a spectrum analyzer with a resolution bandwidth of 1 Hz and an acquisition time of 1 s. The center frequency is 795 MHz and the beatnote linewidth is 2.8 Hz. If two laser systems are assumed to posses the same parameters, this result corresponds to a linewidth of ~2 Hz for each laser.

To minimize the long-term drift of cavity resonance, it is necessary to determine the temperature at which the thermal expansion coefficient of the ULE reference cavity becomes zero. 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 a femtosecond laser frequency comb, whose repetition frequency and offset frequency are linked to a 10 MHz radio-frequency supplied by a hydrogen maser standard [3]. Figure 4(a) shows a measured 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. 4(a). The curve is differentiated and the result with a narrow range of 1°C ~ 2°C is shown in Fig. 4(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 5 shows the measured results, which are obtained over two months. Due to material ageing of the ULE glass, the length of the ULE cavity is changed slightly. The resonance frequency of the laser is also drifted. The curve shown in the Fig. 5 is not as smooth as the curve shown in Fig. 4(a), which is considered to be caused by an ageing drift of the ULE cavity, because it takes several days to set and keep the ULE cavity at each precise temperature. The zero-crossing temperature is around 1.49°C.

Figure 6 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 is used as a frequency reference for optical frequency comb [7].

The ageing drift of the ULE cavity is observed by measuring the resonance frequency of the laser, keeping the cavity at 1.49°C. Figure 7 shows the result. The measurement is gone on about 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.

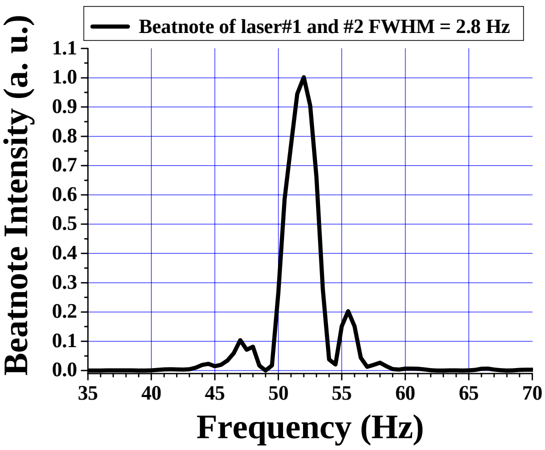

Fig.3. Spectrum of heterodyne beatnote between two laser beams stabilized to two independent ULE reference cavities. Acquisition time is 1s. The resolution bandwidth of the spectrum analyzer is 1Hz. The heterodyne beatnote linewidth is 2.8 Hz, The frequency axis is centered at a difference frequency of 795 MHz.

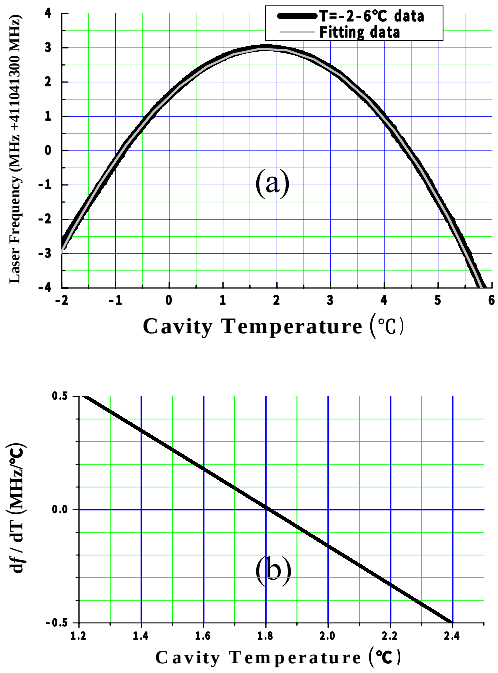

Fig.4. Measurement of absolute frequency dependence on cavity temperature swept from -3°C to 6°C. Figure 4(a) shows the dependence with the frequency axis centered at 411041300 MHz. Figure 4(b) shows a differential of resonance frequency obtained by a cubic polynomial of the fitting curve.

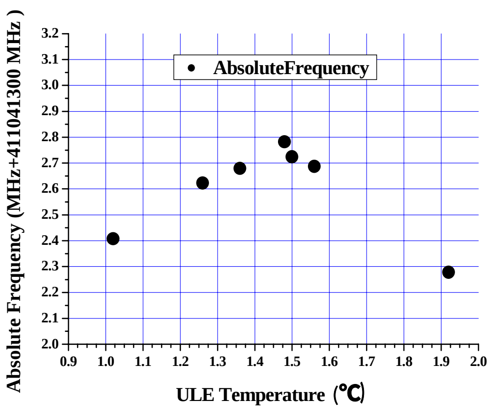

Fig.5. Precise measurement of resonance frequency dependence on the cavity temperature with a range swept from -1°C to 2°C.

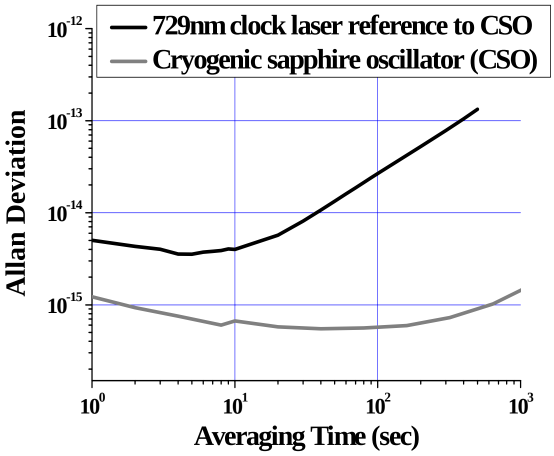

Fig.6. Measured frequency stability of diode laser system (dark curve) and 1GHz signal based on a cryogenic sapphire oscillator used as a frequency reference for the femtosecond laser frequency comb (gray curve).

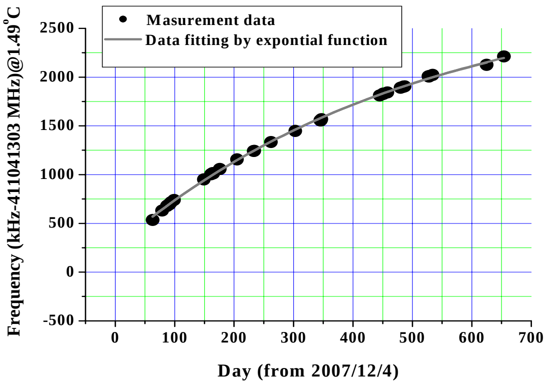

Fig.7. Ageing drift of the ULE cavity: The cavity is kept at 1.49±0.02°C over two years. The clock laser is locked to the cavity and the resonance frequency is measured by a femtosecond laser frequency comb. The data are fitted by an exponential function.

3.2 Fiber Optical Phase Noise Cancellation

For the evaluation of the performance of phase noise cancellation described in §2.3, we measured an out-of-loop heterodyne beatnote signal (from PD3) 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. 7. In Fig. 7(a), the gray 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 7(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 polarization-maintaining single-mode optical fiber of 40 m length. In Fig. 7(a), the servo bandwidth of the phase-locked loop is 2 kHz.

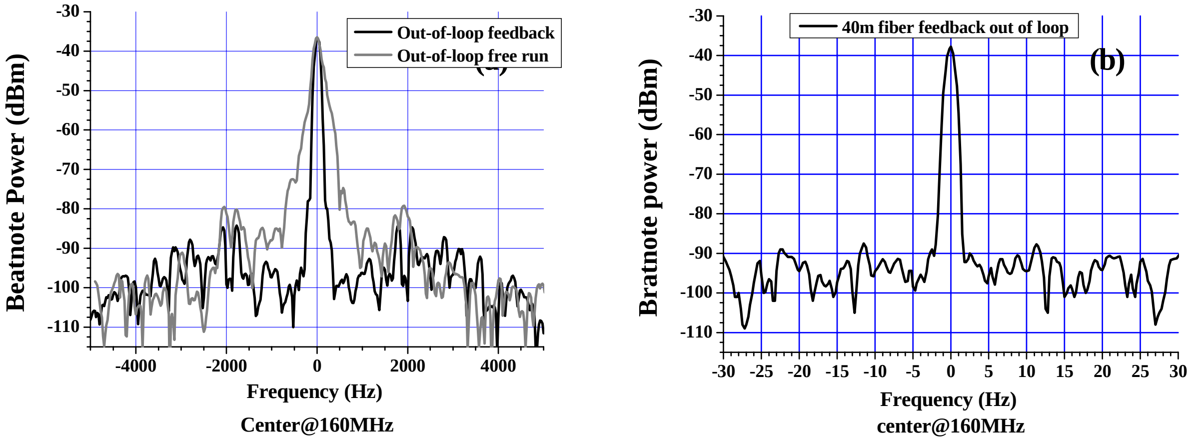

Fig.7. Heterodyne beatnote signal of out of loop. (a): The center frequency is 160 MHz and the bandwidth of the phase-lock loop is 2 kHz. (b): The figure shows that the -3dB full linewidth of the beatnote is 1 Hz, limited by the resolution of spectrum analyzer.

3.3. Compensation of The Laser Frequency Drift

In the § 2.4, we have introduced how to lock the clock laser frequency to the $^{40}Ca^{+}$ transition. Figure 8 shows an example for an Allan deviation of measured frequency. The cryogenic sapphire oscillator is also used as a frequency reference for optical frequency comb. The dots indicate a deviation of the clock laser frequency steered with the $^{40}Ca^{+}$ transitions. In the § 3.1, we have also introduced our laser frequency stability. The long-term drift of the clock laser is only ~ 0.03 Hz/s. It allows us to compensate the frequency once to AOM1 every 100 seconds, using averaging value of the measured transition frequencies of 500 seconds. The squares indicate a deviation of the clock laser frequency without compensation. The result shows that the stability of the compensated frequency is better over averaging times of 100 s. The Allan deviation approaches to 5×10^{-15} over averaging times of 1000 s.

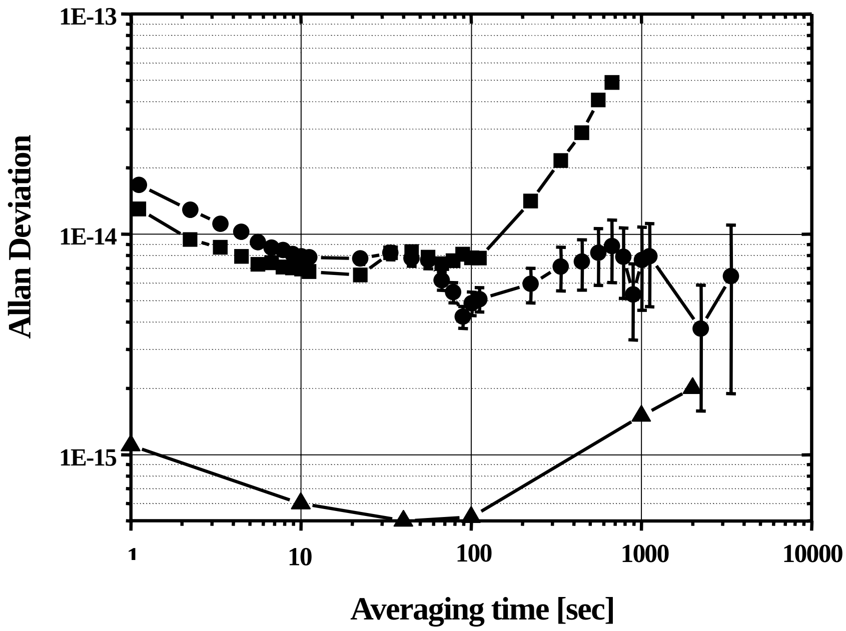

Fig. 8. Allan deviations of the clock-laser frequency. Circles (●) show the deviation of the ULE-cavity-stabilized laser frequency steered with the $^{40}Ca^{+}$ transitions. Squares (■) show that of the ULE-cavity-stabilized laser without compensation of the $^{40}Ca^{+}$ transitions. Triangles (▲) show that of the frequency reference provided by a combination of a Hydrogen maser and a CSO.

4. CONCLUSIONS

A 729 nm diode laser is used for the development of an extremely narrow line 729 nm clock laser for a quadrupole transition of a single $^{40}Ca^{+}$ ion. The laser linewidth is decreased to 2 Hz, evaluated by a heterodyne beatnote between two narrow linewidth lasers that are individually stabilized to two independent ULE reference cavity systems. The ageing drift of the ULE cavity is observed over two years. It shows a decreasing with an exponential function. The long-term frequency drift is successfully minimized to 0.03 Hz/s by keeping the cavity at the zero expansion coefficient temperature. The

Allan deviation is less than 5×10^{-15} at the averaging time of 1 s～10 s. To observe the clock transition, the clock laser light is transmitted to Ca^+ ion vacuum chamber by a polarization-maintaining single-mode optical fiber of 40 m length. Fiber optical phase noise has been canceled. In order to compare with other optical frequency standards or rf frequency standards, the clock laser frequency is locked to the $^2S_{1/2}$-$^2D_{5/2}$ electric quadrupole transition of the single trapped $^{40}Ca^+$ ion. Stable locking has been observed over averaging times of 100 s. The Allan deviation approaches to 5×10^{-15} over averaging times of 1000 s. We are developing an ultrastable laser based on a much higher finesses and vibration insensitive cavity [8]. The ultimate aim is building a clock laser with a subherz linewidth and Allan deviation of $< 1\times10^{-15}$ at 1 s.

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