Frequency Locking and Power Enhancement by Coherent Addition of a Clock Laser for a Portable Multi-$^{40}Ca^+$ Optical Clock

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***Summary*—We construct a frequency locking system for a portable multi-ion optical clock and develop a clock laser whose power is enhanced by the coherent addition method. We reduce the feedback cycle time down to 50 ms, which realizes short-term stabilization with a commercial confocal cavity. To excite the clock transition at 729 nm of multiple ions, we perform coherent addition of 1458-nm optical amplifier outputs and obtain 100 mW at 729 nm by second-harmonic generation.**

Keywords—portable clock; multiple ions; fast feedback; coherent addition

I. INTRODUCTION

A portable optical clock based on multiple $^{40}Ca^+$ ions in a planar ion trap is under development in our group. We aim to obtain an optical clock of 19-inch-rack or less in size and stability of 10^{-13}@1s, which is difficult to achieve with commercially available microwave clocks. The quadrupole transition in $^{40}Ca^+$ ($^2S_{1/2}$ -$^2D_{5/2}$) is used as a clock transition, and a clock laser with a wavelength of 729 nm is servo-controlled to the transition. A larger clock transition signal can be obtained using multiple ions, which enables faster acquisition of an error signal for frequency locking [1]. This scheme allows short-term stabilization of the clock laser with a compact cavity, in contrast to a traditional single-ion optical clock with a relatively large system, that is, a vibration-isolated, temperature-stabilized vacuum system for an optical reference cavity. However, when multiple ions are excited, we cannot focus the clock laser tightly because we need a uniform spectrum for each ion. Therefore, we need to enhance the clock laser power to obtain a laser beam with sufficient intensity and a large Rayleigh length.

In this paper, we report the construction of a system that enables faster feedback with multiple ions, short-term stabilization system with confocal cavity for short-term stabilization test and power enhancement of a clock laser using the coherent addition [2].

II. METHODS/RESULTS

Figure 1 (a) shows the scheme of a portable multi-$^{40}Ca^+$ optical clock. A compact cavity is used for the short-term stabilization of a clock laser, and pulses of the clock laser generated by a shutter irradiate multiple $^{40}Ca^+$ ions in a planar ion trap. Florescence from $^{40}Ca^+$ was collected using a combined imaging lens, which led to an image intensifier followed by a CMOS camera. We calculated the transition probability from the ion image, derived an error signal, and locked the clock laser frequency to the clock transition using an AOM. Two feedback loops will be implemented. One (the other) is to improve the frequency stability (accuracy) with faster (slower) control. Here, we present only the fast feedback loop. In the faster feedback loop, the pulse length is on the order of 1 ms. According to a report on short-term stabilization using a microcavity [3], the feedback cycle time to achieve frequency

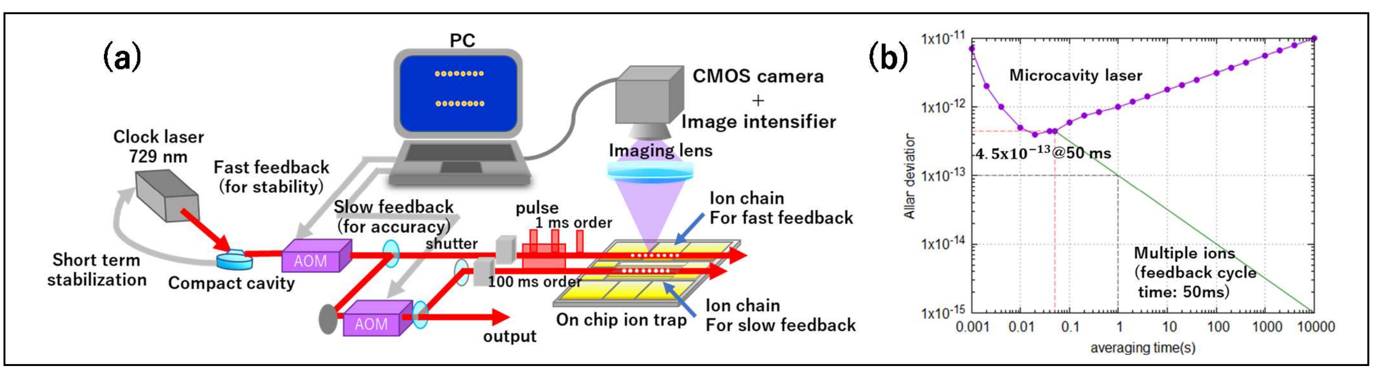

Fig. 1 : (a) A scheme of a multi-$^{40}Ca^+$ portable optical clock. (b) Estimation on averaging time vs Allan deviation of laser frequency when locking to a microcavity [3] and to multiple ions.

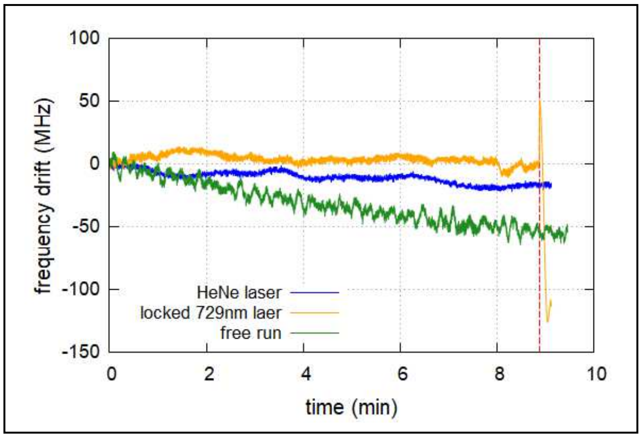

Fig. 2 : Time change for frequency drift of a clock laser acquired by a wavelength meter. Orange: ECDL frequency locked to the clock transition and the cavity. Feedback loop is open when the about 9 min (vertical red dotted line), Blue: HeNe laser used for wavelength meter calibration.

stability of 10^{-13}@1s is estimated to be 50 ms (Figure. 1 (b)). By acquiring the transition probability of multiple ions, we obtain error signal A as follows:

$$A = P(\nu_L + \Delta\nu_L) - P(\nu_L - \Delta\nu_L),$$

where ν_L is the clock laser frequency, P is the transition probability of all ions.

We constructed a system with a feedback cycle time of 50 ms by improving the fluorescence collection efficiency and controlling the pulse length of the clock laser. We locked the frequency of a 729-nm external cavity diode laser (ECDL) to the clock transition. This system uses a confocal cavity for short-term stabilization and fast feedback with cavity length to confirm the frequency locking operation with multiple ions. Figure 2 shows the results of frequency locking acquired using a wavelength meter. The frequency drift of the clock laser was reduced by frequency locking. For faster feedback, it is necessary to shorten the pulse duration for the clock transition. Therefore, the power of the clock laser must be increased.

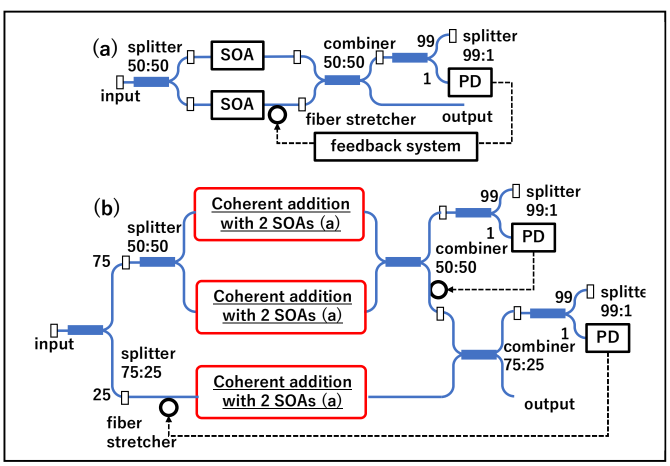

Fig. 3 : (a) A setup of coherent addition by two semiconductor optical amplifiers (SOA). (b) A scheme of coherent addition by six SOAs with two systems (a).

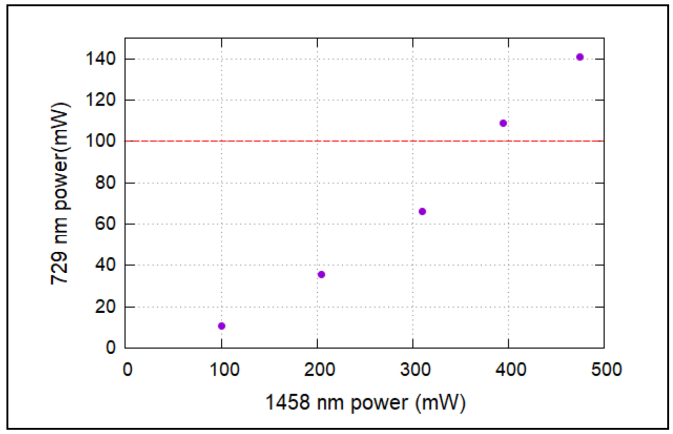

Fig. 4 : Correlation between power amplified by coherent addition system with 6 SOAs at wavelength 1458nm and power wavelength converted to wavelength 729nm. Red: achievement goal 100mW.

Figure 3 shows the setup for improving the power of the clock laser by coherent addition. In this system, the laser power at a wavelength of 1458 nm is enhanced by coherent addition and converted to 729 nm radiation by a second-harmonic generation with a periodically poled lithium niobate (PPLN) crystal. Because of the availability of optical components for optical communication at 1458 nm, a fiber-based system can be implemented. Another merit of this setup is reduction of the residual background in the clock laser spectrum by frequency doubling. In addition, coherent addition enables obtaining higher power than the power limited by the absolute maximum rating of a single semiconductor optical amplifier.

First, as the basic unit of the coherent addition system, we constructed a fiber-based system with two semiconductor optical amplifiers (SOA) (figure 3(a)). The input is split into two ports, amplified at each port, and then superimposed. A fiber stretcher with a piezo element is placed in one port to control the relative phase. By monitoring the photodetector output, we control the fiber stretcher such that the maximum radiation equivalent to the addition of two amplified outputs is obtained at the output port. The phase difference continuously varies with the fluctuating fiber length because of thermal and acoustic noise. To reduce these effects, we covered the system with a thermal-insulation package.

Second, we prepared two basic units to obtain a higher output and constructed their cascade connections (figure 3 (b)). We added a control system to account for the phase difference between the units. The system must compensate for a phase drift larger than that of the basic unit. We developed functions to monitor the locking status and re-lock the system.

Finally, we achieved an operating time of more than 2 hrs with the monitoring and re-locking function. We obtained over 100 mW output at 729 nm against a 400 mW output of the fundamental laser at 1458 nm by frequency doubling and 6 SOAs (Figure 4).

III. DISCUSSION/INTERPRETATION

We reported a system that enables fast feedback, short-term stabilization of the clock laser frequency with a confocal cavity and frequency locking of the 729-nm ECDL frequency to the clock transition using multi-$^{40}Ca^{+}$. Short-term stabilization using a microcavity is required for the optical clock operation. Since the microcavity has a large free spectral range of 10 GHz, the bandwidth of the AOMs is insufficient. A fiber-based electro-optical modulator (EOM) inserted between the 1458 nm ECDL and the microcavity generates a sideband up to 10 GHz, which enables the frequency tuning of the carrier-to-clock transition while the sideband keeps locking to the microcavity. We developed a clock laser with a power of over 100 mW by coherently adding six SOAs. We should be able to reduce the excitation time of the clock transition with the system reported here, which allows a much faster feedback time than with a power of a few milliwatts.

IV. Conclusions

To implement a portable multi-$^{40}Ca^{+}$ optical clock, we constructed a fast feedback system with multiple ions and enhanced the power of the clock laser using the coherent addition method. We obtained a system with a feedback cycle time of 50 ms and a clock laser with a power of 100 mW, and achieved long-term operation. We plan to perform short-term stabilization of the clock laser and clock operation with this setup for an optical clock operation.

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