32nd URSI GASS, Montreal, 19-26 August 2017

A narrow linewidth laser system for strontium and ytterbium optical lattice clocks

Takumi Kobayashi(1)(2), Hajime Inaba(1)(2), Daisuke Akamatsu(1), Sho Okubo(1)(2), and Kazumoto Hosaka(1)(2)
(1) National Metrology Institute of Japan (NMIJ), National Institute of Advanced Industrial Science and Technology (AIST), Umezono 1-1-1, Tsukuba 305-8563, Japan
(2) JST, ERATO MINOSHIMA IOS Project, Umezono 1-1-1, Tsukuba 305-8563, Japan

1. Introduction

At the National Metrology Institute of Japan (NMIJ), we have developed ytterbium and strontium optical lattice clocks [1- 3]. To observe the narrow linewidth clock transition in atoms efficiently, a high-finesse optical cavity is used to narrow the laser linewidth. So far, to operate several optical clocks with different atomic species, ultra-stable optical cavities have to be developed for each atom traditionally, so that it requires a great deal of work with technical skill. An attractive way to overcome the difficulties and to save cost for great optical cavities would be to transfer the linewidth and frequency stability to other frequencies using optical frequency combs [4-6]. Laser linewidth transfer technique based on a high-speed controllable frequency comb stabilized to an ultra-stable laser can be used to stabilize plural lasers with different wavelengths simultaneously using phase lock technique. This scheme would be indispensable tool for measurement of the frequency ratio between different optical clocks. Especially, it is possible to cancel out the frequency instabilities of the ultra-stable laser in the frequency ration measurement, if the clock lasers stabilized to the same ultra-stable laser via a comb interrogate simultaneously on the both clock transitions. In this paper, we explain our ultra-stable lasers and the linewidth transfer scheme by using a fibre based optical frequency comb including the light sources at 578 nm and 698 nm for ytterbium and strontium clock transitions, respectively.

2. Narrow linewidth laser system

We employ a high speed controllable optical frequency comb to transfer the frequency stability of an ultra-stable Nd:YAG laser operating at 1064 nm to clock lasers operating at 578 nm and 698 nm. To achieve reliable phase locks, each phase lock should have a large bandwidth of a fast feedback and large dynamic range of a slow feedback in principle.
The oscillator consists of a mode-locked fibre laser with an erbium-doped fibre and an intracavity electro-optics modulator (EOM), which is inserted into a free space section of the cavity to change the effective cavity length with fast response. Output power from the mode-locked fibre oscillator is split into five branches. The first branch is used to stabilise the carrier envelope offset (CEO) frequency by controlling the pump power of the oscillator. Using the second branch, we can observe a beat note between a component of the fibre comb and the ultra-stable laser operating at 1064 nm. Repetition rate frequency of the comb is stabilized by locking the beat frequency to a reference through feedback to the EOM, so that the comb is stabilized to the master laser operating at 1064 nm. As a slow feedback, the integrated error signal is fed back to a light bulb situated in an aluminium box for the oscillator to control the temperature. The third branch is used to observe the beat between the comb and another ultra-stable laser operating at 1.5 µm. To observe the beat note between the comb and the light source at 578 nm, we use the fourth branch. To generate the comb at around 578 nm, the second harmonic generation(SHG) scheme by using a periodically poled lithium niobate (PPLN) is employed. The fifth branch is used to observed the beat not between the comb and the 698 nm light sources, to narrow the linewidth of the clock laser for the strontium optical lattice clock.
The 578nm light source is generated by an external cavity diode laser (ECDL) operating at 1156 nm combining a SHG scheme provided by another PPLN. To stabilise the laser frequency, the generated light at 578 nm is phase-locked to one of the comb modes, which is frequency-doubled by a PPLN for SHG. The error signal generated by the beat note between the laser and the comb at 578 nm is directly fed back to the current of the ECDL via a loop filter. We also employ a double pass acousto-optic modulator (AOM) set after the PPLN for SHG to provide a slow feedback. Another integrator is also used to control the cavity length of the ECDL by feedback to a Piezoelectric transformer (PZT) put on the grating, so that the frequency stabilisation system can work for long term. From the servo bumps on the beat signal, it is found that the servo bandwidth is about 3.8 MHz.
For the clock transition in the strontium, we employ an ECDL operating at 698 nm. The beat note between the laser and the frequency-doubled comb component at 698 nm generated by another PPLN is fed back to current of the ECDL via a loop filter. The slow feedback error signal after integrated is fed back to the PZT of the ECDL to control the cavity length.

3. Evaluation of the system and discussion

To develop an optical time scale, which would be needed to realise the new SI definition in future, we require a robust system that can keep working for several days at least without any problems on the frequency stabilisation schemes, such as phase

locks. We can operate the developed clock laser system continuously for more than one day. Especially, the master laser and the comb can be operated for more than one week without any problems on the phase locks. As the ULE cavity that is used for stabilisation of the master laser is slightly drifting due to the creep of the glass, the repetition frequency of the comb is also drifting. To reduce the frequency drift, the linear compensation is feedforwarded to an AOM set on the 1064-nm beam pass. Consequently, the effective drift rate of the master laser frequency is now less than 0.5 mHz/s.
To characterise the narrow-linewidth laser system, we measured frequency stability of the beat signal between the stabilised optical frequency comb and the ultra-stable laser at 1.5 μm. Since the ultra-stable laser operated at 1.5 μm was situated in a different room, the 1.5-μm light was transferred to the comb via a 50 m long-optical fibre with employing fibre phase-noise cancellation [7]. The stability of the beat note as measured by the fractional Allan deviation shows that the frequency stability at 1 s almost coincides with the theoretical estimation of the thermal-noise-limited of the cavity [8]. To confirm the relative frequency noise between the comb and the 1.5 μm laser, the beat signal was converted to the voltage and then analysed by measuring the spectrum of the frequency fluctuations. The observed spectral power density of the beat signal almost agrees with the calculated frequency noise induced by the thermal noise on the optical cavity. We have used the clock laser system for atomic spectroscopy and successfully observed the Zeeman components of the $^1S_0$-$^3P_0$ transitions in ^{171}Yb and ^{87}Sr in a homogeneous magnetic field. The observed linewidth of the atomic transitions are about 50 Hz and 10 Hz for ^{171}Yb and ^{87}Sr, respectively. The spectrum linewidth of the ytterbium clock transition is limited due to the power broadening. On the other hand, that of the strontium is Fourier transform limit.

4. Summary

We have developed a novel narrow-linewidth laser system for strontium and ytterbium optical lattice clocks by stabilisation to an optical frequency comb that is locked to an ultra-stable Nd:YAG laser. Using the system, the laser linewidth and frequency stability of the master laser can be transferred to all of the comb modes, so that several lasers operated at different wavelengths can be stabilised simultaneously. The heterodyne beat measured by using another ultra-stable laser shows that the frequency stability of the system is almost limited by the thermal noise on the ULE cavities. The effective cavity drift is now less than 0.5 mHz/s. The phase locks in the reliable system are robust, so that the system can be operated for a few days continuously. We have used the system to observe the narrow linewidth clock transitions in ^{171}Yb and ^{87}Sr.

References

1. T. Kohno, M. Yasuda, K. Hosaka, H. Inaba, Y. Nakajima, and F.-L. Hong, "One-Dimensional Optical Lattice Clock with a Fermionic ^{171}Yb Isotope", *Appl. Phys. Express*, **2**, June 2009, pp. 072501(3 pages).

2. M. Yasuda, H. Inaba, T. Kohnoy, T. Tanabe, Y. Nakajima, K. Hosaka, D. Akamatsu, A. Onae, T. Suzuyama, M. Amemiya, and F.-L. Hong, "Improved absolute frequency measurement of the ^{171}Yb optical lattice clock towards a candidate for the redenition of the second", *Appl. Phys. Express*, **5**, September 2012, pp. 102401(3 pages).

3. D. Akamatsu, H. Inaba, K. Hosaka, M. Yasuda, A. Onae, T. Suzuyama, M. Amemiya and F.-L. Hong, "Spectroscopy and frequency measurement of the ^{87}Sr clock transition by laser linewidth transfer using an optical frequency comb", *Appl. Phys. Express*, **7**, January 2014, pp. 012401(4 pages).

4. K. Iwakuni, H. Inaba, Y. Nakajima, T. Kobayashi, K. Hosaka, A. Onae, and F.-L. Hong, "Narrow linewidth comb realized with a mode-locked fiber laser using an intra-cavity waveguide electro-optic modulator for high-speed control", *Optics Express*, **20**, June 2012, pp. 13769 – 13776.

5. D. Akamatsu, Y. Nakajima, H. Inaba, K. Hosaka, M. Yasuda, A. Onae, and F.-L. Hong, "Narrow linewidth laser system realized by linewidth transfer using a fiber-based frequency comb for the magneto-optical trapping of strontium", *Opt. Express*, **20**, June 2012, pp.16010 – 16016.

6. H. Inaba, K. Hosaka, M. Yasuda, Y. Nakajima, K. Iwakuni, D. Akamatsu, S. Okubo, T. Kohno, A. Onae, and F.-L. Hong, "Spectroscopy of ^{171}Yb in an optical lattice based on laser linewidth transfer using a narrow linewidth frequency comb", *Opt. Express*, **21**, April 2013, pp. 7891 – 7896.

7. L. S. Ma, P. Jungner, J. Ye, and J. L. Hall, "Delivering the same optical frequency at two places: accurate cancellation of phase noise introduced by an optical fiber or other time-varying path", *Opt. Lett.*, **19**, no. 21, November 1994, pp. 1777-1779.

8. K. Numata, A. Kemery, and J. Camp, "Thermal-Noise Limit in the Frequency Stabilization of Lasers with Rigid Cavities", *Phys. Rev. Lett.*, **93**, December 2004, pp. 250602(4 pages).