Absolute Frequency Measurement of $F=4 \rightarrow F'=5$ line of Cesium D2 in an Optical Clock Configuration with Amplified Optical Comb

[1,2]Eok Bong Kim, [1]Sang Eon Park, [1]Chang Yong Park, [1]Won-Kyu Lee, [1]Dai Hyuk Yu, [1]Ho Seong Lee, and [2]Hyuck Cho

[1]Division of Physical Metrology, Korea Research Institute of Standards and Science,
Daejeon 305-600, Korea
[2]Department of Physics, Chungnam National University, Daejeon 305-764, Korea
Email: ubkim@kriss.re.kr

***Abstract*— The selected and amplified optical frequency comb by using diode laser is used in an optical clock configuration to measure the absolute frequency of stabilized ECDL. The ECDL is stabilized to $F = 4 \rightarrow F' = 5$ transition line of cesium D2 line with modulation transfer spectroscopy. The measured frequency is f_{ECDL} = 351 721 960 529 kHz with a statistical uncertainty of 3.5 kHz.**

I. Introduction

Precise measurement of an optical frequency in the visible region is important in metrology as well as in many fundamental applications such as precision spectroscopy and the determination of fundamental physical constants. However, the optical frequency measurement has been a difficult task because the frequency of visible radiation is approximately a factor of 50 000 higher than that of the Cs atomic clock. In the past, an optical frequency measurement is performed with harmonic frequency chains that created successive harmonics from radio frequency provided by a Cs atomic clock. Now, we can use the frequency comb of a mode-locked femtosecond (fs) laser as a ruler to measure the absolute optical frequency [1, 2]. This has resulted in a single-step measurement process of absolute optical frequencies from microwave standard, a tremendous simplification from the traditional frequency chains based on the principle of harmonic synthesis [3].

Usually, two configurations have been exploited for the absolute optical frequency measurement by use of the fs frequency comb; the one is the optical frequency synthesis[2], which the repetition rate and carrier-offset frequency are phase-locked to a local oscillator of which frequency is phase-locked to a Cs atomic clock or a hydrogen maser in the microwave domain, and the other is optical clock configuration where the beat frequency between a stable cw laser and one specific frequency comb component and carrier-offset frequency are phase-locked to a microwave synthesizer [4]. In the first case, the phase noise generated in the phase-locking servo operating in the microwave resulted in a relatively larger frequency noise in the optical frequency measurement compared to the second method due to the large mode number $10^5 \sim 10^6$. Namely, this scheme needs an extremely high quality of local oscillator. In the clock configuration, however, since we detect and phase-lock the beat frequency and carrier-offset frequency simultaneously in the optical frequency domain, there is no phase noise multiplication effect.

In this paper, we describe the experimental results for the absolute frequency measurement of $F = 4 \rightarrow F' = 5$ transition line of cesium D2 line with amplified optical frequency comb by a distributed-Bragg-reflector (DBR) diode laser in an optical clock configuration. The DBR laser is injected by one of the optical comb components and used to improve the beat signal between optical comb and stabilized diode laser.

II. Experimental Setup

The experimental configuration to measure the optical frequency of stabilized diode laser to cesium D2 transition line by using amplified optical frequency comb in an optical clock configuration is shown in Fig 1. Frequency stabilization setup of an ECDL with the Littman cavity configuration is based on the modulation transfer technique of saturation absorption spectroscopy. The ECDL was tuned to operate at 852 nm, which corresponds to the cesium D2 line. In order to minimize the power fluctuation, we used an acousto-optic modulator (AOM). The pump beam is phase-modulated at 5 MHz by an electro-optic modulator (EOM). The pump and probe beams are overlapped to provide a counter propagating beam geometry in a cesium cell. The polarizations of pump and probe beams are linear and orthogonal to each other to reduce the interference between them.

1-4244-0647-1/07/$20.00 ©2007 IEEE

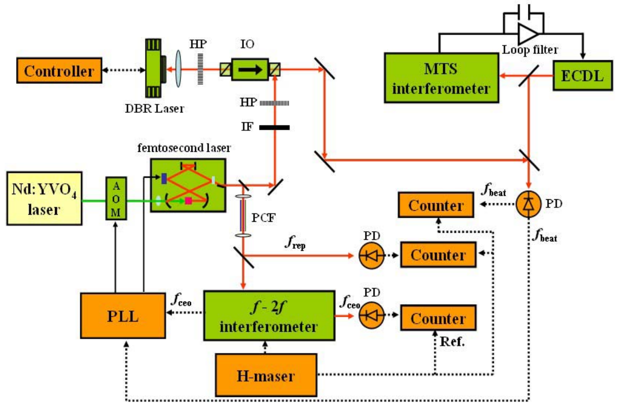

Fig 1 Experimental setup for absolute optical frequency measurement using amplified optical frequency comb in an optical clock configuration (PCF : photonic crystal fiber, PD : avalanche photo-diode, PLL : phase lock loop).

In aligning, we have carefully aligned pump and probe beams in parallel to minimize Doppler shift. Beam diameters of the pump and probe beam are 2.5 mm and 2.8 mm, respectively. To reduce a perturbation from Zeeman shift a µ-metal film was used to shield the cesium vapor cell. The cell was then caged in a box whose temperature is kept at 24 ℃ within 0.01 ℃ variation to keep the vapor pressure constant.

The fs laser generates a 1 GHz pulse train with pulse width as short as 35 fs via Kerr lens mode-locking. The output power of the fs laser operating in the self mode-locked regime is about 700 mW at the pumping power of 5.5 W. The center frequency and spectrum bandwidth of the fs laser are approximately 820 nm and 30 nm, respectively. The output of the fs laser is divided in two by a pellicle beam splitter. The reflected beam with a power 60 mW is used for optical injection locking, while the transmitted is coupled into a 10 cm long photonic crystal fiber to broaden the spectrum over an octave. Using the self-reference technique, the carrier-offset frequency (f_{ceo}) of the fs laser comb is detected and tightly phase-locked to the hydrogen maser.

The details of the performance characteristics of the amplification setup of optical frequency comb with DBR laser is described in Refs. [5], thus we describe here the system briefly. A DBR laser at 852 nm near the cesium D2 line is used as a slave laser. The available output power of the DBR laser is 150 mW, but it is typically operated around 50 mW for this experiment. We used an interference filter with a center wavelength of 825 nm and a transmittance bandwidth of 1.5 nm to select the near wavelength of the slave laser and to prevent optical damage in the slave laser that may result from injection of the fs laser. After passing through the interference filter, the transmitted power of the comb is close to 200 μW, which corresponds to 300 nW per mode, as the number of modes is approximately 600. The fractional frequency noise of the amplified single-mode DBR laser is less than 2.3×10^{-16} at 1 s averaging time and the output power is about 50 mW.

III. ABSOLUTE OPTICAL FREQUENCY MEASUREMENT

The most critical values is the repetition rate frequency (f_{rep}) as it is multiplied by a factor $N \approx 10^5 \sim 10^6$ in the optical frequency synthesis method, when the visible frequency is measured with fs laser of $f_{rep} \approx 10^8 \sim 10^9$ Hz. If f_{rep} is controlled by phase locking to a local oscillator (LO) then, after multiplication of LO phase noise spectral density by factor N^2, this noise becomes a frequency noise in the frequency domain. In this case phase noise of LO is a serious problem, which would require high quality of LO. To measure the absolute frequency f_x, however, one needs to the beat signal between the laser and optical frequency comb for locking f_{rep} to the optical frequency standard and to counter f_{rep} in optical clock configuration method. In this case, the fs comb generator works as a coherent optical divider which transfer the metrological properties of the optical standard to the RF range.

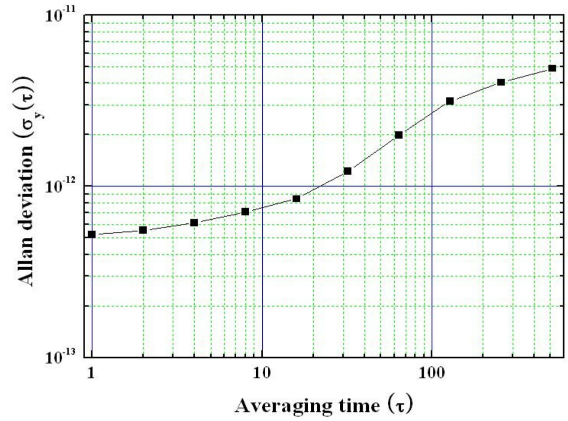

Fig 2 Measured stability of the repetition rate frequency, which phase-locked to frequency stabilized ECDL. For an averaging time of 1 second, the relative Allan deviation is about 5×10^{-13}.

We used a fast avalanche photo-diode to detect the beat frequency (f_{beat}) between the amplified optical frequency comb and frequency stabilized ECDL at 852 nm. We can easily obtain f_{beat} having a signal to noise ratio exceeding 40 dB at 300 kHz resolution bandwidth just by roughly aligning the two laser beams. The detected f_{beat} was then amplified with low noise amplifier to be able to operate the digital phase-detector and frequency counter. The phase-error signal was then fed back to the piezoelectric transducer for frequency stabilization of the f_{rep} and f_{beat} at the same time. When the f_{rep} and f_{beat} are phase stabilized to the hydrogen maser, the frequency fluctuation of f_{rep} at 1 GHz is limited by the stability of our frequency synthesizer. As a result, in optical clock configuration, the whole components of the fs frequency comb are simultaneously phase-locked to frequency stabilized ECDL. The frequency of f_{rep} and f_{beat} are measured for calculation of the absolute optical frequency of $F = 4 \rightarrow F' = 5$ transition line of cesium D2 line by two independent frequency counters which all are referenced to the hydrogen maser. The frequency relation used to calculate the absolute frequency of $F = 4 \rightarrow F' = 5$ transition line of cesium D2 line at 852 nm in the optical clock configuration can be written as

$$f_{\mathrm{ECDL}} = n f_{\mathrm{rep}} \pm f_{\mathrm{ceo}} \pm f_{\mathrm{beat}}, \qquad (1)$$

where the signs of f_{ceo} and f_{beat} can easily be determined by two independent measurement with slightly different repetition rate frequency.

Allan deviation depicted in Fig. 2 shows that the stability of f_{rep} that correspond to the stability of the frequency stabilized ECDL in optical clock configuration. The relative Allan deviation is about 5×10^{-13} for an averaging time of 1 s.

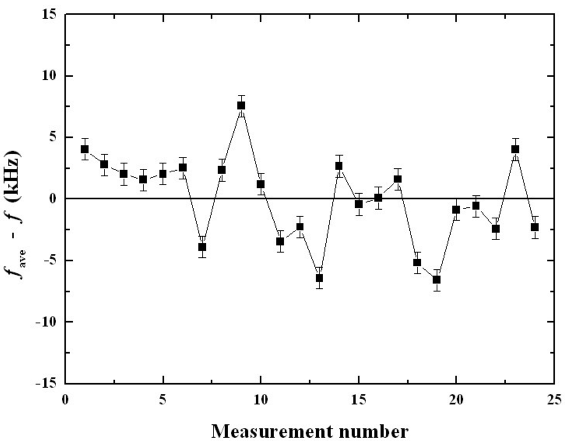

Fig 3 Result of absolute frequency measurement of the *F=4* → *F′=5* transition line of cesium D2 in cesium vapor cell. The average frequency is f_{ave} = 351 721 960 529 kHz.

Figure 3 shows the result of absolute frequency measurement of *F = 4* → *F′ = 5* transition line of cesium D2 line at 852 nm. The y-axis is the frequency deviation of each frequency from the average frequency (f_{ave}). In Fig. 4, the error bar in each data indicates one standard deviation of each frequency measurement, i.e., we consider statistical errors only. The standard deviation of the result is 0.8 kHz which corresponds to the relative standard uncertainty of about 2×10^{-12}. The average frequency was 351 721 960 529 kHz with a statistical uncertainty of 3.5 kHz.

IV. Conclusion

We measured the *F=4* → *F′=5* transition line of cesium D2 line with amplified optical frequency comb by using injection locked DBR diode laser oscillating. In our measurement, an optical clock configuration was used to measure the absolute frequency of frequency stabilized ECDL with modulation transfer spectroscopy. The injection locked DBR laser acts as a single frequency filter and high-gain amplifier. We anticipate that a DBR laser that is injection locked with a single frequency component from an optical frequency comb generator would allow absolute frequency measurement of an optical frequency with high signal-to-noise ratio. The measured absolute frequency of *F=4* → *F′=5* transition line of cesium D2 line was f_{ECDL} = 351 721 960 529 with a statistical uncertainty of 3.5 kHz.

References

[1] D. J. Jones, S. A. Diddams, J. K. Ranka, A. Stentz, R. S. Windeler, J. L. Hall, and S. T. Cundiff, “Carrier-envelope phase control of femtosecond mode-locked lasers and direct optical frequency synthesis,” Science, vol. 288, pp. 635–639, April 2000.

[2] S. T. Cundiff, J. Ye, and Jones, “Optical frequency synthesis based on mode-locked lasers,” Rev. Sci. Instrum. , vol. 72, pp. 3749-3771, July 2001.

[3] H. Schnatz, B. Lipphardt, J. Helmcke, F. Riehle, and G. Zinner, “First Phase-Coherent Frequency Measurement of Visible Radiation,” Phys. Rev. Lett., vol 76, pp 18-21, Jan. 1996.

[4] L-S. Ma, L. Robertsson, S. Picard, J-M. Chartier, H. Karlsson, E. Prieto, and R. S. Windeler, “The BIPM laser standards at 633 nm an 532 nm simultaneously linked to the SI second using a femtosecond laser in an optical clock configuration,” IEEE. Trans. Instrum. Meas., vol 52, pp 232-235. April 2003.

[5] S. E. Park. E. B. Kim, Y.-H. Park, D. S. Yee, T. Y. Kwon, and C. Y. Park, “Sweep optical frequency synthesizer with a distributed-Bragg-reflector laser injection locked by a single compoonent of an optical frequency comb,” Opt. Lett., vol. 31, pp. 3594-3596, Dec. 2006.