Light Shift Detection Using a Multiple Photodetection Method Suitable for a Chip-Scale Atomic Clock

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***Summary*—In this study, we demonstrated light shift detection in a running atomic clock using the multi-photodetection method. This method enables the observation of atomic resonances with different intensities using the intensity distribution of the laser beam. As it requires only two photodiodes to detect light shifts, it is easily applicable to miniature vapor-cell-based atomic clocks such as chip-scale atomic clocks and miniature atomic clocks.**

Keywords—coherent population trapping; chip-scale atomic clock; laser; VCSEL; light shift; intensity distribution

I. Introduction

Devices that provide precise time and frequency information are required for applications such as time stamps of sensed data, network synchronization, GNSS jamming, and spoofing robustness. In these applications, compact vapor-cell-based atomic clocks such as chip-scale atomic clocks (CSACs) and miniature atomic clocks (MACs) are widely used.

Light shift is known to be the primary factor in the long-term frequency stability degradation of CSACs and MACs [1]. It is the frequency shift caused by the laser, which excites and observes atomic resonance. If the conditions of the laser source or optical system do not change over time, the light shift would be constant; however, in reality, they do change over time, and the light shift also changes and deteriorates the long-term stability. Therefore, methods for the suppression, measurement, estimation, or compensation of light shift are required to improve long-term stability.

Herein, we propose the multi-photodetection (MPD) method as an atomic resonance observation method to measure the light shift [2], [3]. MPD is based on the Gaussian-shaped intensity profile of a collimated laser beam. Multi-photodetectors simultaneously observe atomic resonances with different intensities in the Gaussian intensity profile. The light shift can be estimated by comparing the resonance frequencies of the two photodetectors. The MPD method for measuring light shift does not require mechanics or intensity change systems.

In this study, we demonstrated the real-time light shift detection of a vapor-cell-based atomic clock using MPD. Subsequently, we estimated the light shift in the operating atomic clock using the MPD method.

II. MPD Methods and Experimental Setup

Fig. 1 shows an illustration of the MPD method and experimental setup. The multi-photodiodes for MPD used a 16-element photodiode array (S15158, Hamamatsu Photonics K.K.). This photodiode array had a detection area of 2.0 × 0.7 mm with a spacing of 0.1 mm. A single-mode vertical-cavity surface-emitting laser with a wavelength of 895 nm on the Cs-D1 line was used as a laser source. The output laser was collimated to a diameter of 6.4 mm and circularly polarized to excite the coherent population trapping resonance. To demonstrate the MPD method for CSACs, we used an MEMS microcell vapor cell, which contained Cs and 18.7 kPa of Ne. The frequency of the temperature-compensated crystal oscillator (TCXO) was locked to the atomic resonance by the error signal obtained by Ch. 3 of the PD, and the light shift was monitored using the error signal obtained by Ch. 2 of the PD. The laser intensity at Ch. 2 was half that at Ch. 3. We used an ND filter to change the light shift and measured it using the MPD method.

III. Results

Fig. 2 shows the frequency fluctuation of the TCXO, error signals, and PD voltages of the photodiodes of Ch. 3 and Ch. 2 when the ND filters were switched every hour. To verify the

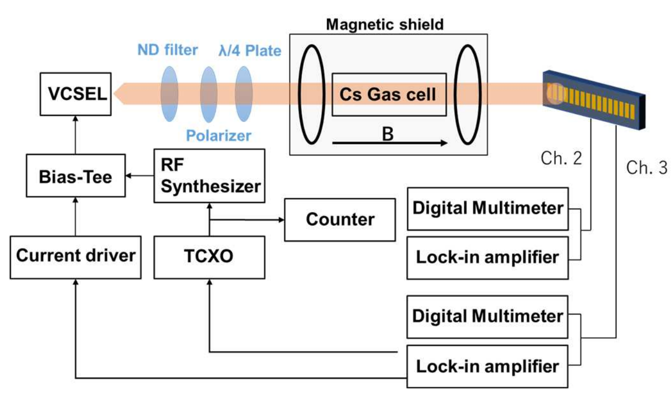

Fig. 1. Experimental setup for an atomic clock using the MPD method.

detection of the light shift by MPD, an RF power of −2.5 dBm, where the light shift coefficient was large, was employed. A light shift was observed because the frequency was increased by switching the ND filters. Subsequently, because the Ch. 2 error signal was not zero, a light shift was observed. The DC level of the Ch. 2 error signals increased in the negative direction as the light shift increased. These results indicate that the MPD method can detect and observe light shifts in the operating atomic clock.

IV. Conclusions

In this study, we demonstrated real-time light shift detection in an operating atomic clock using the MPD method. The MPD method requires only two photodiodes and allows for the measurement of a light shift in the operating atomic clock; further, it can be used for zero-light shift detection, such as active light shift stabilization [4], to improve the long-term stability of CSACs and MACs,.

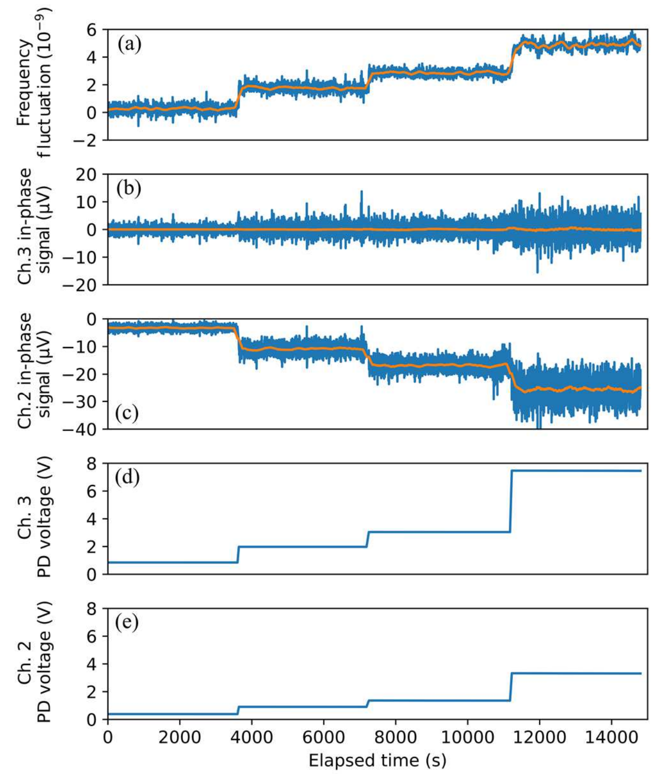

Fig. 2. (a) Frequency fluctuation of the TCXO, (b) error signal of Ch. 3 PD, (c) error signal of Ch. 2 PD, (d) transmitted light voltage of Ch. 3 PD, and (e) transmitted light voltage of Ch. 2 PD.

References

[1] O. Kozlova, J.-M. Danet, S. Guerandel, and E. de Clercq, "Limitations of long-term stability in a coherent population trapping Cs clock," IEEE Trans. Instrum. Meas., vol. 63, no. 7, pp. 1863–1870, July 2014. doi: 10.1109/TIM.2014.2298672.

[2] M. Fukuoka, A. Hanatani, and S. Goka, "Light shift measurement method using photodiode array applicable to chip scale atomic clocks," in The 82nd JSAP Autmun Meeting 2021, Online, September 2021, pp. 21a-P05-1.

[3] M. Fukuoka, A. Hanatani, and S. Goka, "Novel light-shift measurement method with multiple photo detectors for gas-cell based atomic clocks," in Proc. of 2022 Joint conference of the European Frequency and Time Forum & the IEEE International Frequency Control Symposium, Paris, France, unpublished.

[4] V. Shah, P. D. Schwindt, V. Gerginov, S. Knappe, L. Hollberg, and J. Kitching, "Active light shift stabilization in modulated CPT clocks," in 2006 IEEE International Frequency Control Symposium and Exposition, Miami, FL, USA, June 2006, pp. 699–701. doi: 10.1109/FREQ.2006.275473.