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Investigations on simultaneous detection of CPT resonances by two-phase detection

2 位相検波による複数の CPT 共鳴の同時検出の検討

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1. Introduction

Coherent Population Trapping (CPT) spectroscopy, which detects microwave transition by all-optical system, is very useful for compact atomic clocks and magnetometers that are attractive for wireless communication and sensor network[1]. The CPT atomic clocks utilize a clock transition of the hyperfine structure transition of alkali atoms. Since the clock transition frequency is insensitive to magnetic field, the atomic clock has tolerance to external disturbance of magnetic field[2]. On the contrast, the CPT atomic magnetometers utilize the a Zeeman transition whose frequency is sensitive to magnetic field[3]. The magnetic field is estimated from measuring the frequency difference between clock and the Zeeman transition. The both devices are on basis of measuring atomic transition. However, because the signals of the clock and Zeeman transitions can not be measured in the same time by conventional CPT resonance detection, the both functions of atomic clock and magnetometers can not be realized simultaneously. One of the reason for the limitation is narrow measurement bandwidth of conventional FM detection. Although the FM detection is generally used in CPT atomic clocks and magnetometers, the measurement bandwidth is up to several hundreds Hz shown in dot blue line of Fig. 1. Since allocating the two measurement bands that measure the clock and Zeeman transitions to the tight frequency band is difficult, the two measurements can not be isolatedly executed.

In this paper, we propose a two-phase modulation of CPT resonance for simultaneous detection of clock and Zeeman transitions. The two-phase modulation is a detection method of CPT resonances by lock-in detection in two different frequencies. Since the phase modulation provides a several order of magnitude broader measurement bandwidth than to conventional FM detection as shown in Fig. 1 [4], it is easily possible to isolate the frequency bands of the two lock-in measurements. To validate the effectiveness of the proposed method, we numerically calculated the error signals based on the density matrix analysis of Λ-type three level system simulated the hyperfine structure of ^{87}Rb D_1

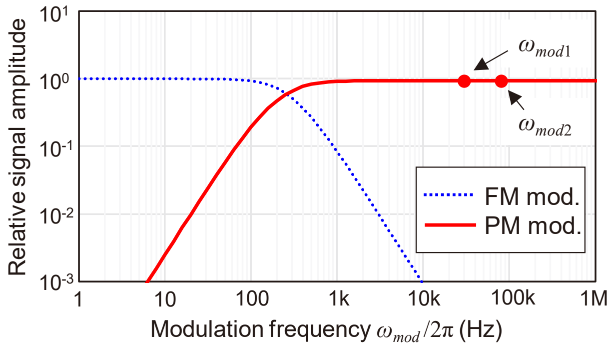

Fig. 1 Calculated signal amplitude-frequency characteristics of error signal. Blue dot line and Red solid line are FM and PM detection, respectively.

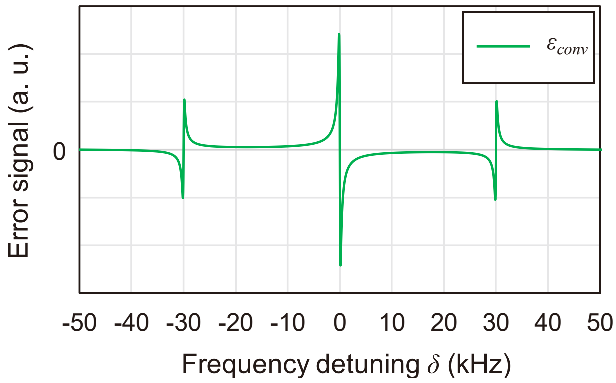

Fig. 2 Calculated error signal of single-phase modulation ($\omega_{mod1}/2\pi$ = 30 kHz)

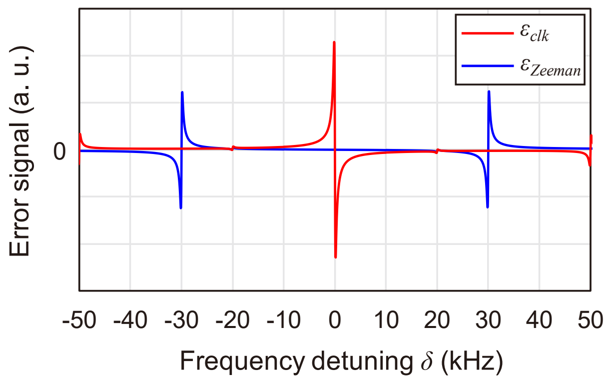

Fig. 3 Calculated error signals of two-phase modulation ($\omega_{mod1}/2\pi$ = 30 kHz, $\omega_{mod2}/2\pi$ = 80 kHz)

line[5]. As a result, it is indicated that the each error signal can be separately obtained by the two-phase modulation with weighted adding and subtracting the error signals.

2. Two-phase modulation detection

The frequency of CPT resonance generally is measured by synchronous detection to obtain high signal to noise ratio of CPT resonance. The modulation frequency of phase modulation is set higher than several kHz to keep the signal amplitude of the error sinal(Fig. 1). The two-phase modulation detection has two synchronous detection with two different modulation frequencies $\omega_{mod1}, \omega_{mod2}$ to measure two tansitions in the same time. However, the raw error signals $\varepsilon_{\omega_{mod1}}, \varepsilon_{\omega_{mod1}}$ obtained by two synchronous detection can not provide the separated correction signal of two transitions because the spectrum of two error signals is coupled with each other at the modulation frequencies. For suppressing the spectrum coupling, we focus on asymmetry of the raw error signals at modulation frequencies. By utilizing asymmetry of two error signals, we can obtain the two signals ε_{clk}, ε_{Zeeman} separately by weighted adding and subtracting the two error signals of $\varepsilon_{\omega_{mod1}}, \varepsilon_{\omega_{mod1}}$

$$\varepsilon_{clk} = w_{clk,1}\varepsilon_{\omega_{mod1}} + w_{clk,2}\varepsilon_{\omega_{mod2}}$$
$$\varepsilon_{Zeeman} = w_{Zeeman,1}\varepsilon_{\omega_{mod1}} - w_{Zeeman,2}\varepsilon_{\omega_{mod2}} \qquad (1)$$

where, w are weighting parameters that are determined by each modulation index. Because the recent synchronous detection is performed by digital processing and the error signals are obtained as digital value, this weighting process can be accomplished with simple digital circuit.

The two error signals were numerically calculated based on density matrix analysis modeled Λ-type three level system that has two ground states and common excited state. The numerical calculation is performed using Galerkin spectrum method that is widely employed for the numerical analysis of piezoelectric mechanical resonators such as quartz [6,7].

3. Calculated results

Figure 2 shows the calculated error signals of CPT resonance with single phase modulation ($\omega_{mod}/2\pi = 30$ kHz). Since there are large sub-peaks caused by side-bands of phase modulation at $\delta = \pm\omega_{mod}$, the error signal of clock transition is sensitive to magnetic field assuming Zeeman sub-levels are located at $\delta = \pm\omega_{mod}$. On the other hand, the error signals with two-phase modulation ($\omega_{mod1}/2\pi$ = 30 kHz, $\omega_{mod1}/2\pi$ = 80 kHz), shown in Fig. 3, shows that ε_{clk} has no sub-peak at $\delta = \pm\omega_{mod1}$ because $\varepsilon_{\omega_{mod1}}$ and $\varepsilon_{\omega_{mod2}}$ cancel each other by weighted sum by the asymmetry. In the same way, ε_{Zeeman} has no peak at $\delta = 0$. Therefore, since the two error signals are insensitive each other, the proposed method allows that the correction signals ε_{Zeeman}, ε_{clk} could be individually obtained.

4. Conclusions

We proposed two-phase modulation detection of CPT resonance for simultaneous measuring clock and Zeeman transitions. The proposed method is two-synchronous detection at different modulation frequencies and provides the two separated correction signals by processing weighted addition and subtraction of the raw error signals. We numerically calculated the error signals based on the density matrix analysis of simple Λ-type three level system. The frequency spectrum of error signals were derived from Galerkin spectrum method that is that is fast and precise calculation algorithm. The result shows that the two error signals can be separately obtained by weighted addition and subtraction considering the asymmetry of the error signals.

Acknowledgment
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