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IMPROVEMENT OF FREQUENCY ACCURACY In A SEMICONDUCTOR LASER PUMPED ^{87}Rb ATOMIC CLOCK

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<ABSTRACT>

Light shift of rubidium atomic clock was accurately measured. By controlling the laser frequency detuning based on the results of the measurements, the microwave frequency inaccuracy of a rubidium atomic clock was reduced to $\pm 3.2\times 10^{-11}$.

I. Introduction

Highly precision rubidium (^{87}Rb) atomic clocks have been required for various applications, e.g., the signal sources for GPS satellites. For the improvement of their performances, the ^{87}Rb atomic clock pumped by a semiconductor laser have been investigated[1][2].

In this paper, we proposed a new technique to improve frequency accuracy in the ^{87}Rb atomic clock pumped by a semiconductor laser.

II. Measurements of Light Shift

Figure 1 shows a block diagram of a ^{87}Rb atomic clock pumped by a semiconductor laser. The optical-microwave double resonance affects the electric field of laser light transmitted through the ^{87}Rb vapor. The amplitude transmissivity (T) can be defined as $T = e^{-\delta - i\phi}$, where δ and ϕ are the amplitude attenuation and phase shift, respectively. The phase of the transmitted laser light is modulated by means of modulation of microwave signal at angular frequency ω_m. Therefore, due to the nonlinear susceptibility of the three-level ^{87}Rb atoms, the several harmonic components ($n\omega_m$; $n=1,2,3,\ldots$) would be induced in the light power ($I_T(t)$) detected by photodetector[3][4][5]. $I_T(t)$ can be written as

$$I_T(t) = I_0\sum_{n=0}^{\infty}[C_n\cos(n\omega_m t) + S_n\sin(n\omega_m t)], \quad (1)$$

where C_n and S_n are the in-phase and the quadrature components, respectively. Such a component can be measured by using phase sensitive detection technique. The measured spectral profile of these components are shown in Fig.2. As the profiles of fundamental components (C_1 , S_1) and 3rd harmonic components (C_3, S_3) cross the abscissa at the transition frequency, they can be used as frequency discriminators. The microwave frequency should be stabilized at the zero-cross point of these frequency discriminators. However, the dynamic stark effect by the electric field of pumping light would induce the light shift,i.e., the shift in microwave transition frequency[6]. Since this frequency is used as a frequency reference for ^{87}Rb atomic clocks, the light shift would limit their frequency accuracy as well as frequency stability. Precise measurements of the light shift have been rather difficult in the conventional ^{87}Rb atomic clocks because of the complicated spectral profile of the ^{87}Rb lamp. However, it can be measured more precisely by using a highly coherent semiconductor lasers.

Figure 3 shows the relations between the microwave frequency shift $\Delta\nu_{HFS}$ of the center of the spectrum and the laser frequency detuning $\Delta\nu_L$ from the center frequency of the $5S_{1/2}$, F=1 -> $5P_{3/2}$ transition. In particular, it is first observed that the microwave frequency shift is also increased with increasing the laser power density at the laser frequency detuning $\Delta\nu_L=0$ as being shown in Fig.4. This phenomenon can be explained as the shift of energy level of the $5S_{1/2}$, F=2 when the laser frequency was tuned to the resonance frequency of the $5S_{1/2}$, F=1 -> $5P_{3/2}$ transition.

III. Self-Tuning System for Improving Frequency Accuracy

For the improvement of the microwave frequency accuracy, the laser frequency should be controlled based on the results of measurements of the light shift described in II. To this end, we proposed a novel technique to evaluate the microwave frequency shift by using a deformation of spectral shape. As shown by Fig.5, the spectral lineshape of S_1, used as a frequency discriminator, was deformed and lost its symmetry by detuning the laser frequency. We defined an asymmetrical factor ΔS as the area difference between S_+ and S_- in Fig.6(a). As shown in Fig.6(b), the value of this factor ΔS was directly calculated by a computer. From the results of Figs.3 and 6, difference between the exact transition frequency in ^{87}Rb and the microwave frequency of ^{87}Rb atomic clock, i.e., $\Delta\nu_{HFS}$ can be estimated by given value of ΔS. It is should be noted that this technique does not require a separate reference frequency source, therefore, this system can be referred as self-tuning system.

Drift of the controlled atomic clock frequency was compensated by the self-tuning system (see Fig.1) at every 10 minutes. Working time of self-tuning system was about 2 minutes. The microwave frequency inaccuracy as low as $\pm 3.2\times 10^{-11}$ was obtained as shown in fig.7. This value is 1/10 times that of conventional ^{87}Rb atomic clocks[7].

IV. Summary

Light shift of rubidium atomic clock was accurately measured. The light shift induced by the laser power density was first observed even when the laser frequency detuning was exactly tuned to the transition frequency for zero power level of the laser. Self-tuning system, which did not require a separate reference frequency source, was constructed to compensate for the effect of light shift. The microwave frequency inaccuracy obtained by using this novel technique was as low as $\pm 3.2\times 10^{-11}$, which is 1/10 times that of conventional ^{87}Rb atomic clocks.

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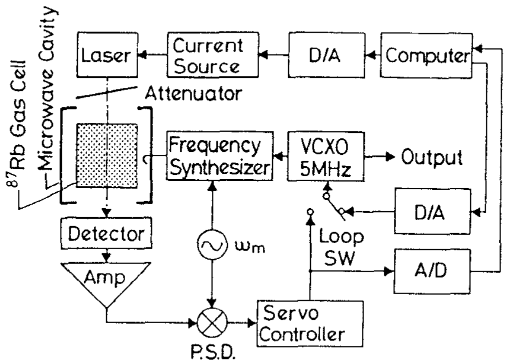

Fig.1 A block diagram of the ^{87}Rb atomic clock pumped by a semiconductor laser.
P.S.D. : Phase sensitive detector.
Amp : Post-detector Amplifier.
ω_m : Angular frequency of a low frequency for microwave frequency modulation.
D/A : Digital to analogue converter.
A/D : Analogue to digital converter.

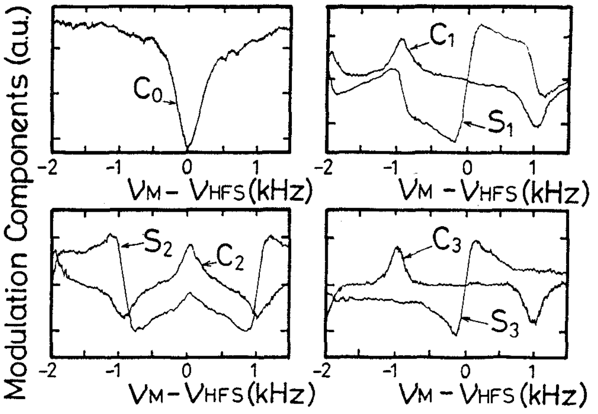

Fig.2 The spectral profiles of modulation components on the microwave frequency ν_M. The modulation frequency was fixed at $\omega_m/2\pi = 1$ kHz.
ν_M : The microwave frequency.
ν_{HFS} : The microwave transition frequency.

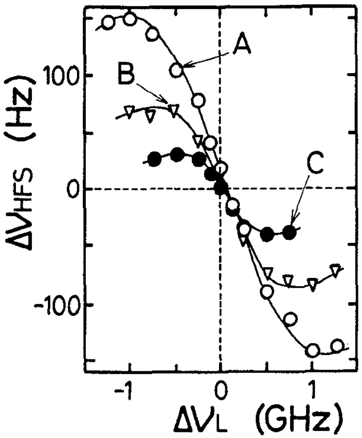

Fig.3 Light shift $\Delta\nu_{HFS}$ induced by laser frequency. The laser power density was fixed at 1520 μW/cm^2(A,○), 380 μW/cm^2(B,▽), and 152 μW/cm^2(C,●).
$\Delta\nu_L$: The laser frequency detuning.
$\Delta\nu_{HFS}$: The microwave resonance frequency shift.

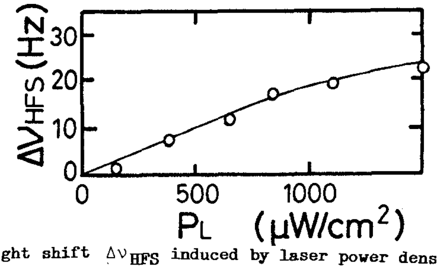

Fig.4 Light shift $\Delta\nu_{HFS}$ induced by laser power density. The laser frequency was tuned to the $5S_{1/2}$,F=1 -> $5P_{3/2}$ transition.
P_L : The laser power density.

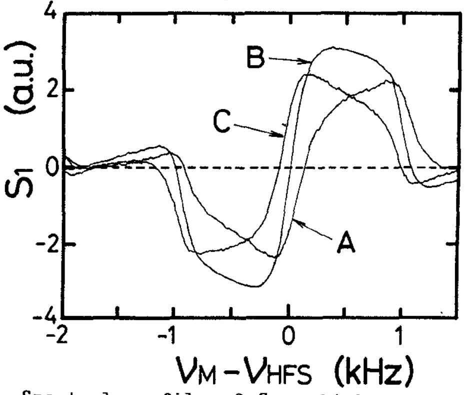

Fig.5 Spectral profile of S_1, which was used as a frequency discriminator for microwave frequency control. The laser frequency detuning was fixed at -750 MHz(A), 0 MHz (B), and 750 MHz(C).

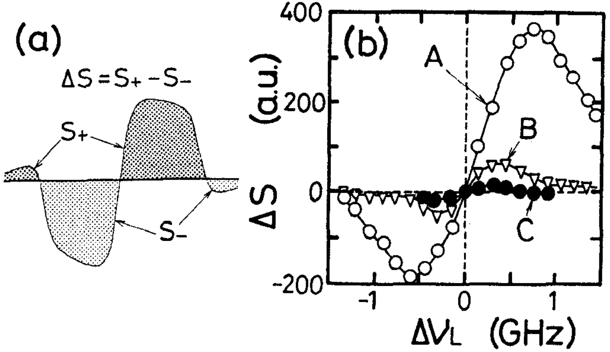

Fig.6 (a) The definition of the asymmetrical factor ΔS.
S_+ : The integration of the spectral profile with positive amplitude.
S_- : The integration of the spectral profile with negative amplitude.
(b) Relation between the asymmetrical factor ΔS (defined by Fig.6 (a)) and the laser frequency detuning $\Delta\nu_L$. The laser power density was fixed at 1520 μW/cm^2(A,○), 380 μW/cm^2(B,▽), and 152 μW/cm^2(C,●).
$\Delta\nu_L$: The laser frequency detuning.
ΔS : The asymmetrical factor.

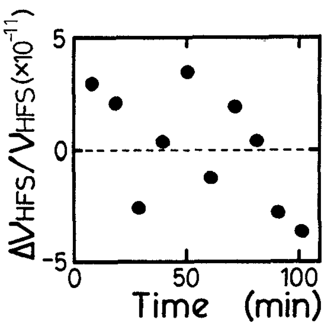

Fig.7 Normalized variation of difference between the exact transition frequency in ^{87}Rb and the microwave frequency of ^{87}Rb atomic clock.
$\Delta\nu_{HFS}/\nu_{HFS}$: The microwave frequency inaccuracy.