Characteristics of an Optically Pumped Cs Frequency Standard at the NRLM

SHIN-ICHI OHSHIMA, YASUHIRO NAKADAN, TAKESHI IKEGAMI, YASUKI KOGA,
R. DRULLINGER, AND L. HOLLBERG

***Abstract*—We report some characteristics of an optically pumped Cs frequency standard developed at the National Research Laboratory of Metrology (NRLM). The short term frequency stability was estimated to be 1.1 × $10^{-12}/\sqrt{\tau}$ when we used the optical feedback technique for laser diode stabilization. Frequency shifts due to microwave power and pumping conditions were measured and their characteristics are described.**

I. INTRODUCTION

OPTICAL pumping and detection methods are expected to improve the performance of a Cs atomic beam frequency standard [1]. At the NRLM, an optically pumped Cs frequency standard is under development. The system design is based on the conventional NRLM standard, NRLM-II [2]. Some preliminary experiments to confirm the fundamental functions were carried out [3], and the performance characteristics of the standard are now being measured.

In this paper, we report some characteristics of the Ramsey resonance spectrum, frequency stability, and frequency shifts due to microwave power and optical pumping conditions. The frequency stability depends on the frequency noise of the laser diodes which are used for optical pumping and detection. Spectral narrowing of the lasers by optical feedback is effective in reducing the laser frequency noise [4], [5] and increasing the clock stability.

The microwave power shift originates from various causes such as end-to-end and distributed cavity phase shift, and first-order Doppler shift. These are all related to the velocity distribution and trajectories of the Cs atoms. A velocity distribution in a conventional Cs frequency standard is limited by its beam optics; the trajectories of Cs atoms are bent by magnets. On the other hand, the velocity distribution of the optically pumped standard is near Maxwellian and the trajectories are bent only by gravity and light pressure. Therefore, it is expected that the characteristics of microwave power shift will be different from conventional standards. Because the microwave power shift is the largest uncertainty of the NRLM-II standard [2], it is very important for us to investigate its effects for the optically pumped system. We have measured the microwave power shift as a function of the laser pump power and different optical pumping schemes.

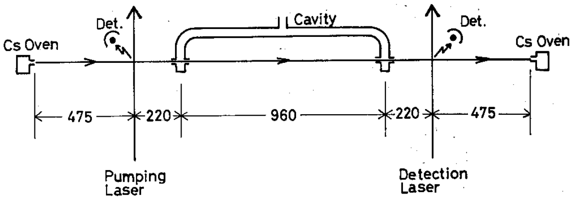

Fig. 1. Major dimensions of the optically pumped frequency standard (unit in millimeters).

II. APPARATUS AND EXPERIMENTAL CONDITIONS

Major dimensions of the beam tube are shown in Fig. 1. The microwave cavity length is 0.96 m, and the effective cross section of the Cs beam is limited by the cavity holes through which the Cs atomic beam passes (3.2 mm × 3.2 mm). The microwave cavity is of the *U*-type, operating in a TE_{01N} mode. Other details of the standard's structure are shown in [3]. The *C*-field is transverse to the atomic beam direction, and its strength is 7.9 A/m with a measured inhomogeneity of $|\delta H_{\max}|/H_0 = 0.3$ percent. The frequency shift due to this inhomogeneity is less than 5×10^{-15} and is not now a serious problem. The room temperature is maintained at 23 ± 1°C.

In this experiment, we used either the $F = 4 \rightarrow F' = 4(\sigma)$ or the $F = 4 \rightarrow F' = 3(\sigma)$ transition for the optical pumping, and the $F = 4 \rightarrow F' = 5\ (\sigma)$ transition for the optical detection where, F indicates the hyperfine components of the ground state $6^2S_{1/2}$, and F' indicates the hyperfine components of the state $6^2P_{3/2}$, as shown in Fig. 2. The $F = 4 \rightarrow F' = 5(\sigma)$ detection scheme is useful because it provides large signals (owing to the cycling transition), and the problem of the high sensitivity to the laser noise is solved by the optical feedback lock. The linewidth of the laser diode is normally 10–15 MHz without the optical feedback. We confirmed that the spectral width with optical feedback is less than 1 MHz, and it might be around 1 kHz [4]. The light beam cross section of the laser beam is about 2 mm × 4 mm, and we usually

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S. Ohshima, Y. Nakadan, T. Ikegami, and Y. Koga are with the National Research Laboratory of Metrology, 1-1-4, Umezono, Tsukuba-shi, Ibaraki 305, Japan.

R. Drullinger and L. Hollberg are with the National Institute of Standards and Technology, Boulder, CO 80303.

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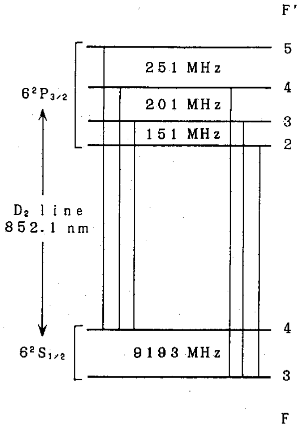

Fig. 2. Energy levels of ^{133}Cs associated with D_2 transition.

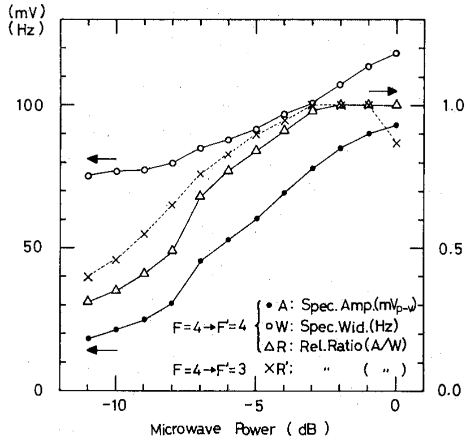

Fig. 3. Microwave power dependence of the Ramsey resonance spectrum. A, W, and R show peak-to-valley amplitude in millivolts, full width at the half amplitude, and the ratio of the amplitude to the width, respectively. The maximum of R is normalized to 1. The pumping scheme for A, W, and R was $F = 4 \rightarrow F' = 4$. The pumping scheme for R' was $F = 4 \rightarrow F' = 3$.

adjust the longer axis of the laser beam cross section perpendicularly to the Cs beam in order to irradiate all the atoms of the Cs beam.

III. RAMSEY RESONANCE SPECTRUM

The shape of the Ramsey spectrum is sensitive to the microwave power. Fig. 3 shows an example of the amplitude (peak-to-valley, ● : A) and the spectral width (full width at half amplitude, ○ : W) of the Ramsey spectrum as a function of microwave power. For these data the pumping scheme is $F = 4 \rightarrow F' = 4$. The shape can also depend on the laser power, but it is relatively constant for pumping powers of 2 ~ 10 mW. The microwave power is scaled to 0 dB which is arbitrarily taken as the power required for the maximum size of the Ramsey resonance. The spectral width of the microwave resonance in the optically pumped system is more sensitive to the microwave

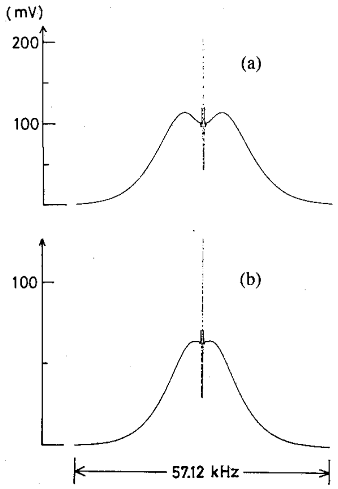

Fig. 4. Rabi–Ramsey spectra at the microwave powers of (a) 0 dB and (b) −5 dB.

power than conventional standards, because the velocity distribution of the optically pumped standard is broader. When the microwave power is decreased, the slow atoms contribute relatively more to the resulting resonance. We find that the spectral width decreases about 35 percent when the microwave power changes from 0 to −10 dB. The ratio of the amplitude to the width ($\Delta : R$) is unchanged between 0 and −3 dB and then gradually decreases (the maximum of this ratio is normalized to 1.0). When we use $F = 4 \rightarrow F' = 3$ pumping, the optimum power reduces by −1 dB. The optimum power depends on the optical pumping scheme because of the velocity dependence of the optical pumping and detection.

Fig. 4(a) and 4(b) shows the Rabi–Ramsey spectra at 0 and −5 dB, respectively.

IV. FREQUENCY STABILITY

We measured the frequency stability with the microwave power 5 dB below optimum and the width of the Ramsey resonance was about 90 Hz as shown in Fig. 3. The pumping and the detection laser powers were maintained at about 7.5 and 3.2 mW, respectively, for this stability measurement. We used a digital servo control system for the microwaves and adjusted the modulation width to the full width at half amplitude of the Ramsey spectrum.

The stability was measured by a phase comparison with a commercial Cs atomic clock. The stability that we measured is shown in Fig. 5. We performed the measurements under two different conditions. One is without the optical feedback (○ : Without OF) and the another is with the optical feedback (● : With OF). As the number m of measurements for long τ is limited, we indicated error bars, $\sigma(\tau)/\sqrt{m}$ [6]. The data can be fitted by $\alpha/\sqrt{\tau}$; this gives the lines $L1$ and $L2$, which correspond to $1.5 \times 10^{-11}/\sqrt{\tau}$ and $6.3 \times 10^{-12}/\sqrt{\tau}$, respectively. The mea-

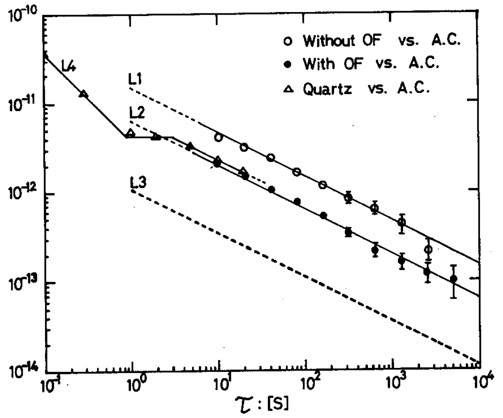

Fig. 5. Frequency stability obtained by comparing with a commercial reference atomic clock (AC). *L1* shows the frequency stability of the optically pumped standard without optical feedback locking of the laser diodes. *L2* shows the stability of the atomic clock used as the reference. *L3* is an estimated frequency stability of the optically pumped standard with optical feedback locked lasers.

sured stability was improved by the optical feedback, but the improvement was only about 2.4 times. On the other hand, the *S/N* ratio was improved by a factor of 14 [5]. This indicates that *L2* is limited by the stability of the reference atomic clock. We compared a quartz oscillator and the reference atomic clock for short times τ to confirm this idea. Because the stability of the quartz oscillator is better than the reference atomic clock for $\tau < 30$ s, the stability around $\tau = 10 \sim 20$ s indicates the stability of the reference atomic clock. *L4* agrees with *L2*, so *L2* must indicate the stability of the reference atomic clock. If the stability is actually improved by the *S/N* ratio as expected, we would obtain a clock stability of

$$\sigma(\tau) = 1.1 \times 10^{-12}/\sqrt{\tau}$$

between $\tau = 10$ and 10 000 s. This stability is comparable to the best conventional Cs laboratory standards.

V. Frequency Shift Due to Microwave Power and Pumping Conditions

We measured the frequency shifts by using the reference atomic clock for comparison. The modulation width was always adjusted to the width at the half-amplitude of the spectrum as shown in Fig. 3. The *C*-field direction was kept from north to south. Only one Cs beam direction was used in this experiment to determine the general feature and the magnitude of the frequency shift. The results are shown in Fig. 6. The microwave power induced frequency shift was measured every 2 dB from 0 to −10 dB. The measurements were performed with three different optical pumping configurations. For the data represented by ● and ○, the pump laser was tuned to the $F = 4 \rightarrow F' = 4$ transition and their laser powers were 9.8 and 1.8 mW, respectively. The pumping scheme for the data × was $F = 4 \rightarrow F' = 3$ and its laser power was 9.8 mW. The detection laser power was always kept at 4.5 mW. We did not use the optical feedback locking in this measurement and the measuring time was 3 h. The measurement uncertainty is estimated to be on the order of $\pm 2 \times 10^{-13}$ judging from the stability of Fig. 5.

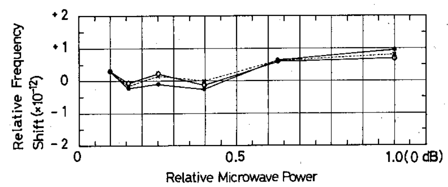

Fig. 6. Frequency shifts due to microwave power. The pumping scheme for ● and ○ is $F = 4 \rightarrow F' = 4$ and the laser powers are 9.8 and 1.8 mW, respectively. The pumping scheme for × is $F = 4 \rightarrow F' = 3$ and its laser power is 9.8 mW.

All three pumping conditions have the same microwave power shift within the measurement error. Therefore, the effects of the actual pumping conditions, which will produce the different velocity distributions (through the different pumping efficiencies) and beam bending are not detected at this measurement level.

In the optically pumped frequency standard, there is a light shift due to the fluorescence light produced at the pumping area, and the intensity and the frequency of the fluorescent light depend on the pumping conditions. The light shift has been calculated by Brillet [7] and Shirley [8]. When we apply Shirley's formula to our standard using the intensity observed at the pumping area and dimensions as shown in Fig. 3, the light shift is calculated to be less than 8×10^{-15}. Our experimental result is consistent with that.

The microwave power shift increases above −4 dB and the maximum shift is about 1×10^{-12} at 0 dB. The details of the general pattern of the shift is not simple, but we cannot discuss the details yet because the measurement uncertainty is not small enough. The details like that will be made more clear by the beam reversal experiment [9]. In addition, it will be interesting to investigate the frequency shift in extremely low microwave power, because the trajectory of the Cs beam will be bent by the gravity and light pressure.

VI. Conclusions

We draw the following conclusions.

1) Based on the measured *S/N* in detection, we estimate that a frequency stability of $1.1 \times 10^{-12}/\sqrt{\tau}$ could be achieved in the optically pumped standard when optically stabilized lasers are used.

2) We observed a microwave power dependent frequency shift, which increased above −4 dB of microwave power and is about 1×10^{-12} at 0 dB. At the $\pm 2 \times 10^{-13}$

level and with limited measurements the microwave power shift did not show a dependence on the optical pumping conditions.

The very good stability we infer from the measured S/N shows promise for the ultimate performance of the optically pumped standard.

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