Experimental Study of $^{85}$Rb CPT Atomic Clocks for Low-Power Operation

Shigeyoshi Goka
Tokyo Metropolitan University
goka@eei.metro-u.ac.jp

Abstract

An $^{85}$Rb vapor-cell atomic clock based on a coherent population-trapping (CPT) resonance for low power operation is proposed. The choice of $^{85}$Rb rather than conventional $^{87}$Rb is dictated by the lower ground-state hyperfine-splitting frequency, which leads to less than one-half operating power of laser modulation sources and more effective RF circuit designs. This paper describes outline and features of the $^{85}$Rb atomic clock, the observation of the CPT resonance in an $^{85}$Rb/$^{87}$Rb mixed vapor cell, and the results of frequency stabilities of a pilot system. The experiments were performed with the sealed vapor cells, the vertical-cavity surface-emitting laser (VCSEL), and the optical and electrical devices.

The results show that the CPT resonances at both $^{85}$Rb and $^{87}$Rb can be separately observed, and the line width of each CPT resonance is less than 100 Hz. The frequency stabilities of the output signals were $< 7 \times 10^{-12}$/day for $^{85}$Rb and $< 6 \times 10^{-12}$/day for $^{87}$Rb, respectively. In addition, the RF modulation signal power for $^{85}$Rb was 2 dB less than that of $^{87}$Rb because of modulation efficiency characteristics of the VCSEL.

1. Introduction

Inexpensive and relatively compact frequency references are available commercially. In these references, an alkali-vapor cell with an external microwave cavity for proving the transitions between ground and excited states is used [1]. Since the microwave cavity size is decided by the transition wavelength of the alkali atoms, keeping cavity and gas cell temperature constant requires few Watts of power consumption because of its large volume. There are limitations of miniaturization and low power consumption as far as using a cavity.

For portable equipment such as global-positioning system receivers, in-field telecommunication devices, and many kinds of measuring instruments, low-cost compact frequency references with low power consumption and good long-term stability ($< 10^{-11}$/day) have been in demand [2]. As atomic clocks based on coherent population trapping (CPT) meets this demand, CPT based atomic clocks with a vertical-cavity surface-emitting laser (VCSEL) have been extensively progressed [2-13]. Since one of the most advantageous features of a CPT resonance is that it does not require a large microwave cavity [14,15], the physics package of an atomic clock can be fabricated in a small volume. In addition, a selection of alkali-atoms is not limited by its transition frequency between ground and excited states. For these CPT-based atomic clocks, $^{85}$Rb and Cs vapors are typically used and their required source radio frequency (RF) is 3.4 and 4.6 GHz, respectively. In general, a higher frequency requires more power in electrical circuits, therefore, reducing the RF requires less power-consumption than that required by conventional CPT clocks.

In this paper, I propose an $^{85}$Rb vapor-cell CPT atomic clock for low power operation. The choice of $^{85}$Rb rather than conventional $^{87}$Rb was dictated by the lower ground-state hyperfine-splitting frequency, which leads to less than one-half of the required power of the laser modulation sources and more effective RF circuit designs.

2. Three level $\Lambda$ system in alkali atoms

The CPT resonance can be excited in so-called $\Lambda$ systems with two long-lived ground states $|g_1>$ and $|g_2>$ and one excited state $|e>$ coupled by bichromatic light fields, as shown in Fig. 1. The wavelength of the light field between $|g_2>$ and $|e>$ for D1 and D2 lines, and the ground-state hyperfine-splitting frequency $f_{\text{hf}}$, are listed in Table 1.

The $f_{\text{hf}}$ for $^{85}$Rb is 3.0 GHz [16], which is less than one-half that of $^{87}$Rb and one-third that of Cs. Using $^{85}$Rb vapor decreases $f_{\text{hf}}$ generated from a local oscillator to excite the CPT resonance. The CPT resonances of $^{85}$Rb and $^{87}$Rb can be observed in the
same gas cell because a natural mixture of Rb isotopes consists of both $^{85}$Rb and $^{87}$Rb atoms.

3. Measurement system

In the CPT atomic clock test system, the natural mixture of Rb gas cell was used. The gas cell with 3 cm length consists of a buffer gas, and its temperature was controlled at 38°C to stabilize the CPT resonant frequency. A small homogeneous magnetic field of 2.3-µT flux density parallel to the optical axis was generated around the vapor cell. A single-mode vertical-cavity surface-emitting laser (VCSEL) with a 780-nm wavelength was driven by a dc injection current at 1 mA and was modulated by an RF source to generate first order sidebands around the laser carrier to excite Rb between the ground state $^5S_{1/2}$ and the excited state $^5P_{2/3}$. The RF modulation frequency was set at 1.5, 3.0, 3.4, and 6.8 GHz, which were both at the full- and half-ground-state hyperfine frequencies of $^{85}$Rb and $^{87}$Rb. For the 1.5- and 3.4-GHz modulation frequency, two first order sidebands were used to excite from two ground states $|g_1>$ and $|g_2>$ to $|e>$. For the 3.0- and 6.8-GHz modulation frequency, the carrier and a first order sideband were used. The linearly polarized optical output from the VCSEL was sent through a quarter wave plate to create a circular polarization and was attenuated by natural-density filters. At the entrance of the vapor cell, a 3.4-µW/cm² circular-polarized light beam of 4 mm in diameter was emitted. The intensity transmitted through the cell was detected with a photodiode.

4. Absorption Profiles of Rb gas cell

The Rb absorption profile scanned around the D2 line is shown in Fig. 2. In the natural Rb absorption profile, both $^{85}$Rb and $^{87}$Rb profiles are overlapped. Because the isotope ratio of $^{85}$Rb/$^{87}$Rb is 2.6, the F=2 and F=3 absorptions of $^{85}$Rb were larger than that of F=1 and F=2 of $^{87}$Rb. The frequency was normalized by the center frequency between the F=2 and F=3 absorptions of $^{85}$Rb. With RF modulation applied, the

Table 1. Wavelength of light field for D1 and D2 lines and ground-state hyperfine-splitting frequency.

<table>
<thead>
<tr>
<th>Atom</th>
<th>D1 line</th>
<th>D2 line</th>
<th>f_{hfs}</th>
<th>f_{hfs}/2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cs</td>
<td>894 nm</td>
<td>852 nm</td>
<td>9.2 GHz</td>
<td>4.6 GHz</td>
</tr>
<tr>
<td>$^{87}$Rb</td>
<td>795 nm</td>
<td>780 nm</td>
<td>6.8 GHz</td>
<td>3.4 GHz</td>
</tr>
<tr>
<td>$^{85}$Rb</td>
<td></td>
<td></td>
<td>3.0 GHz</td>
<td>1.5 GHz</td>
</tr>
</tbody>
</table>

Figure 2. Absorption profile for Rb vapor with RF modulation.
absorption profiles changed significantly because of the generated laser side-bands. In the experiments, the input RF power was optimized as the amplitudes of the CPT resonances were maximized.

For the RF modulation of $^{87}\text{Rb}$ atoms, several absorption maximums were present at both 6.8 and 3.4 GHz because of large $^{85}\text{Rb}$ absorptions. For the 6.8-GHz modulation, CPT resonances were observed at two maximum points where $^{87}\text{Rb}$ vapor had F=1 and F=2 absorptions, indicated by arrows in the Fig. 2. For the 3.4-GHz modulation, which was the half-ground-state hyperfine frequency, the center frequency between F=1 and F=2 was located in the middle of the absorption slope near the absorption maximum. At the center frequency, the CPT resonance was observed; however, the resonance amplitude was a few times lower than that for the 6.8-GHz modulation because the laser light was used for the excitation of $^{85}\text{Rb}$ atoms. In addition, the long-term frequency could not be measured because the laser stabilization feedback loop could not be locked at this laser wavelength.

For $^{85}\text{Rb}$ atoms, CPT resonances were observed at both 3.0- and 1.5-GHz modulations. An example of the CPT resonance for the 1.5-GHz modulation, which was measured using an averaging function of an oscilloscope with a 1-kHz frequency modulation for the RF source around the CPT center frequency, is shown in Fig. 3. The CPT resonance frequency was shifted upward 1.6 kHz as a result of buffer gas collisions and light shift, and the full width at half-maximum (FWHM) was ~ 50 Hz.

5. Frequency deviation of Rb CPT atomic clocks

In the long-term frequency measurements, we used a 10-MHz oven-controlled crystal oscillator (OCXO) for controlling the RF signal generator as a reference source. A lock-in at 100 kHz was used to lock the laser to the Rb absorption maximums indicated by arrows in Fig. 2, and a lock-in at 125 Hz was used to lock the OCXO, which in turn controls the frequency of the RF source. The frequency counter was locked by a Cs standard, and the OCXO output frequency was measured continuously every 2 seconds.

Figure 4 shows the frequency deviation of the Rb CPT clock operated at a 6.8-GHz (+3.0 dBm) modulation for $^{87}\text{Rb}$ and 1.5-GHz (-3.5 dBm) for $^{85}\text{Rb}$. The values were normalized by each start frequency, and $1\times10^{-10}$ was added to the values of $^{85}\text{Rb}$ and subtracted from the values of $^{87}\text{Rb}$ for clear observation.

Figure 3. CPT Resonance for $^{85}\text{Rb}$.
Center frequency was 1.517867839GHz.

Figure 4. Frequency deviations of $^{85}\text{Rb}$ and $^{87}\text{Rb}$ CPT.

Figure 5. Allan deviations for Rb vapor CPT atomic clocks.
Allan deviations estimated from the measured data is shown in Fig. 5. The long-term stabilities were $< 4.0 \times 10^{-12}$/day for $^{85}$Rb and $< 3.5 \times 10^{-12}$/day for $^{87}$Rb. In the case of $^{85}$Rb, the ground-state hyperfine frequency was nearly half that of $^{87}$Rb; therefore, the frequency shift caused by environmental fluctuations was roughly twice as sensitive as that of $^{85}$Rb. For example, the measured $^{85}$Rb and $^{87}$Rb frequency temperature-coefficients of the Rb gas cell were $1.2 \times 10^{-9}$ and $0.6 \times 10^{-9}$/K, respectively. The frequency fluctuations might be affected by these sensitivity differences even though cell and laser temperatures were controlled.

These results indicate that the $^{85}$Rb CPT atomic clock is able to keep demanded long-term stability $\sim 10^{-11}$/day, and that choosing operation modes was available only by changing the RF frequency in the same system. $^{85}$Rb was suitable for low power operation, and $^{87}$Rb was suitable for highly accurate operation.

6. Conclusions

An $^{85}$Rb vapor-cell CPT atomic clock for low power operation was proposed. The results show that the CPT resonances for both $^{85}$Rb and $^{87}$Rb can be observed separately in the natural mixture of an Rb vapor cell. The frequency stabilities of the 10-MHz OCXO output signals for each CPT resonance were less than $4.0 \times 10^{-12}$/day for $^{85}$Rb and $3.5 \times 10^{-12}$/day for $^{87}$Rb. The RF modulation signal power for $^{85}$Rb was 2.0 dB less than that of $^{87}$Rb, which was 3.4 GHz, because of the modulation efficiency characteristics of the VCSEL. In addition, it is possible to switch between low-power and highly-accurate operation modes by only changing the RF frequency.

7. References