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STUDY OF THE FREQUENCY STABILITY OF LASER-PUMPED RB GAS-CELL FREQUENCY STANDARDS[1]

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ABSTRACT

We report the improvement of short term stability ($5 \cdot 10^{-13}\ \tau^{-1/2}$) that has been obtained with a laser-pumped passive gas-cell frequency standard.

Three types of lasers, including extended cavity (EC), solitary and DBR lasers, have been used with different stabilization schemes. Their amplitude modulation (AM) noise and phase modulation (PM) noise have been measured and compared.

The requirements on the *accuracy* and on the *stability* of their frequency stabilization have been established by light shift measurements which were performed with simultaneous heterodyne detection of the laser frequency. The use of the D_1 line instead of the D_2 line of Rb^{87} is also discussed. The possibility of simultaneously making the two light shift coefficients ($\Delta\nu_{clock} / \Delta I_{laser}$ and $\Delta\nu_{clock} / \Delta\nu_{laser}$) zero is described. Some limitations due to the microwave synthesizer are presented. Finally, clock stability measurements are presented and discussed.

Keywords : Rubidium passive frequency standard, laser optical pumping, light shift, noise.

1. INTRODUCTION

The paper contains four sections. The first section defines our goals and recalls the frequency stability limits of passive laser-pumped rubidium frequency standards. The second section displays our analysis of the two major potential sources of instabilities: the laser and the microwave interrogation. The third section presents the short term stability obtained with different types of laser diodes and discusses the long term behavior of the clock. The conclusions are given in the fourth section.

Our goal is to build a "super local oscillator" with a short-term stability near $1 \cdot 10^{-14}\ \tau^{-1/2}$ for use in clocks based on laser cooled atoms and ions.

Presently, we are using an atomic resonator containing a buffer-gas cell. This delivers a signal compatible with an ultimate short term stability of $1 \cdot 10^{-13}\ \tau^{-1/2}$. This stability can be called the "shot noise limit" since it is the theoretical limit obtained from the shot noise of the detected light. This noise is typically 1 pA/√Hz, when the DC light intensity has been optimized.

Different processes involving both the laser and the microwave radiation introduce frequency instabilities which are above the shot noise limit. The following section details the phenomena related to the laser and briefly describes some effects due to the microwave radiation. This last aspect will be presented with more details in a separate communication (Ref. 2).

2. CLOCK INSTABILITY SOURCES

2.1 Limitations from the laser

The laser radiation alters the clock stability by adding noise on the photodetector and by modifying its frequency via the light shift effect. Each of these processes results from different mechanisms which are discussed separately below.

2.1.1 Noise on the photocurrent

We have measured the photocurrent noise on the signal detector in typical operating conditions with three types of laser sources. The results obtained at a Fourier frequency of 300 Hz (typical clock modulation frequency) are summarized in Table 1.

These results show that the intrinsic intensity noise of all the laser sources is not significantly higher than shot noise (column 1). However, the values measured after the laser beam has passed through the vapor (column 2) indicate that additional noise is present on the detection photocell. This noise, which can be one order of magnitude higher than shot noise (with the EC laser and the solitary laser), is due to laser phase noise combined with the atomic absorption (Ref. 3).

Table 1 *Photocurrent noise on the photodetector with different types of laser diodes and locking schemes (shot noise = 1 pA/√Hz). The 1st and 2nd columns display the noise before and after the rubidium cell*

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respectively. The last column is obtained with the noise cancellation technique described in the text.

Laser and *locking type*	Noise before Rb [pA/√Hz]	Noise after Rb [pA/√Hz]	Noise with cancellation [pA/√Hz]
Solitary *current mod.* *70* kHz	2	30	3
EC *piezo mod.* *7* kHz	2	30	3
DBR *sideband* *12* MHz	1.5	2	1.7

According to theory (Ref. 3), this additional noise should be proportional to the laser linewidth. Our results are in apparent disagreement with this prediction since the noise obtained with the EC laser is as high as the noise obtained with the solitary laser. We attribute this discrepancy to low frequency phase fluctuations of the laser, probably due to mechanical instabilities in the extended cavity system.

The total intensity noise perturbs the clock stability because it adds noise to the signal. For this reason, it is possible to improve the clock stability using a *passive* noise cancellation (Ref. 4). As described in (Ref. 1), this could be successfully implemented in a laser-pumped Rb clock.

As can be seen in the last column of Table 1, the shot noise can be approached with the three laser systems.

2.1.2 Light shift

Many studies on light shift in laser-pumped rubidium clocks have been reported (Ref. 5). In particular, the light shift is a limiting factor on the clock performance (Ref. 6). In this research, we have focused on the problem of *accuracy* and *stability* of the laser frequency, and its relationship with the clock short term and long term behavior.

With Rb^{87}, the laser frequency can be tuned either to the D_1 transition $S_{1/2} \rightarrow P_{1/2}$ (795 nm) or to the D_2 transition $S_{1/2} \rightarrow P_{3/2}$ (780 nm). D_2 has the advantage of more efficient optical pumping (and thus a higher double resonance signal). D_1, as will be shown, could be more interesting as far as the medium and long term performance is concerned.

Since there are two ground state hyperfine sublevels (F=1 and F=2), two groups of transitions are available for both D_1 and D_2. F=2 is usually chosen to be depopulated since the double resonance signal is higher by a factor of 5/3 for an almost unchanged light shift. Thus, the problem of selecting the optimal transition for clock operation is reduced to the choice between two possibilities : D_1 or D_2.

Figure 1 displays the light shift measurement corresponding to the first option. The laser frequency (current) has been swept through the atomic transition at different light intensities. The closest line appears to be approximately 140 MHz higher than the unique zero light shift frequency ($\nu_{LS=0}$). In order to fine tune the laser frequency, we shifted the laser frequency with an acousto-optic modulator (AOM) in a double pass setup. The light shift was then measured at different detuning frequencies, which were precisely known by heterodyne detection of the beat node against a second laser. The result obtained are shown on Figure 2.

Figure 2 is in good agreement with Figure 1 and provides a very precise measurement of the light shift coefficient. From this coefficient, we have deduced the requirements on the *accuracy* and the *stability* of the laser frequency tuning for a specified clock stability. These requirements are given in Table 2.

Table 2 *Summary of the requirements on the laser accuracy and stability deduced from the light shift coefficient of the D_1 transition of Rb^{87} ($\delta\nu_{clock}$ = relative clock frequency fluctuation, $\Delta\nu_{laser}$ = laser frequency detuning from the zero light shift frequency, $\delta\nu_{laser}$ = laser frequency fluctuation, δI_{laser} = laser intensity change).*

Light shift coefficient $\frac{\delta\nu_{clock}}{\Delta\nu_{laser} \cdot I_{laser}}$	$\frac{1 \cdot 10^{-11}}{MHz \cdot \mu A}$
Short term stability *laser frequency stability* ($\delta\nu_{laser}$ so that $\delta\nu_{clock} < 10^{-13}$?)	$\delta\nu_{laser}$ < **5 kHz**
Long term stability *laser frequency stability* ($\delta\nu_{laser}$ so that $\delta\nu_{clock} < 10^{-12}$?)	$\delta\nu_{laser}$ < **50 kHz**
laser frequency (tuning) accuracy ($\Delta\nu_{laser} \rightarrow \delta I_{laser}=1\% \rightarrow \delta\nu_{clock} < 10^{-12}$?)	$\Delta\nu_{laser}$ **< 2.5 MHz**
Closest saturated line	**20 MHz / 140 MHz** D2 / D1

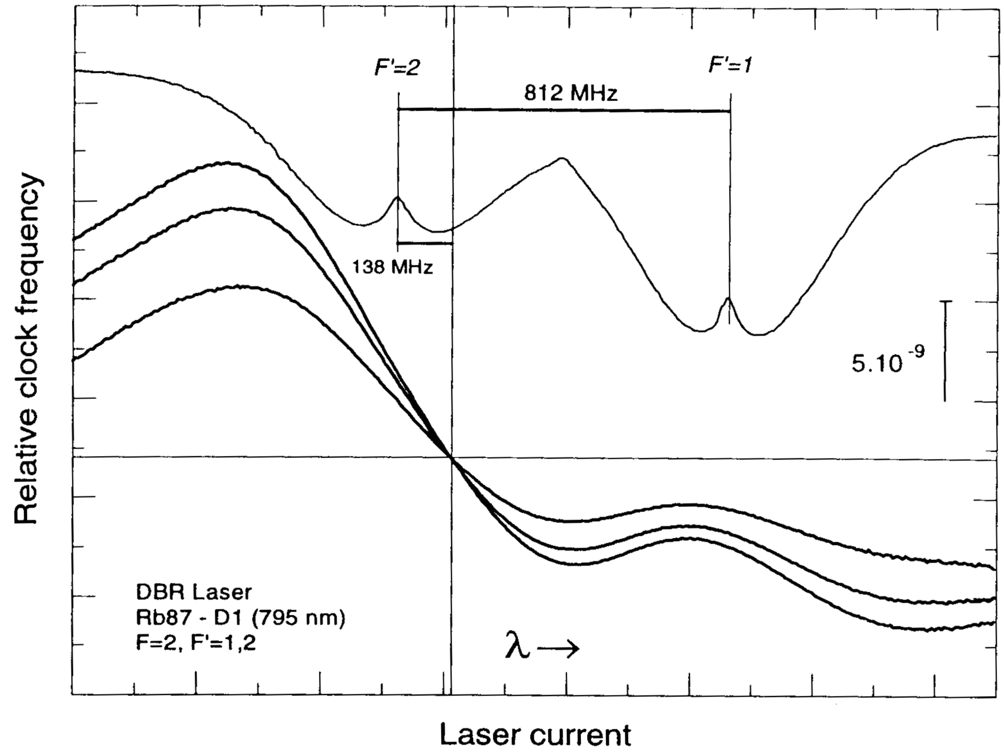

Figure 1 **Light shift coefficient of the D_1 transition of Rb^{87}.** *The lower curves show the clock frequency with three different light intensities, 4.3, 5.7, and 6.4 μA approximately (1 μA ≈ 4 μW/cm²). The upper curve displays the saturated absorption of a separate evacuated Rb^{87} cell.*

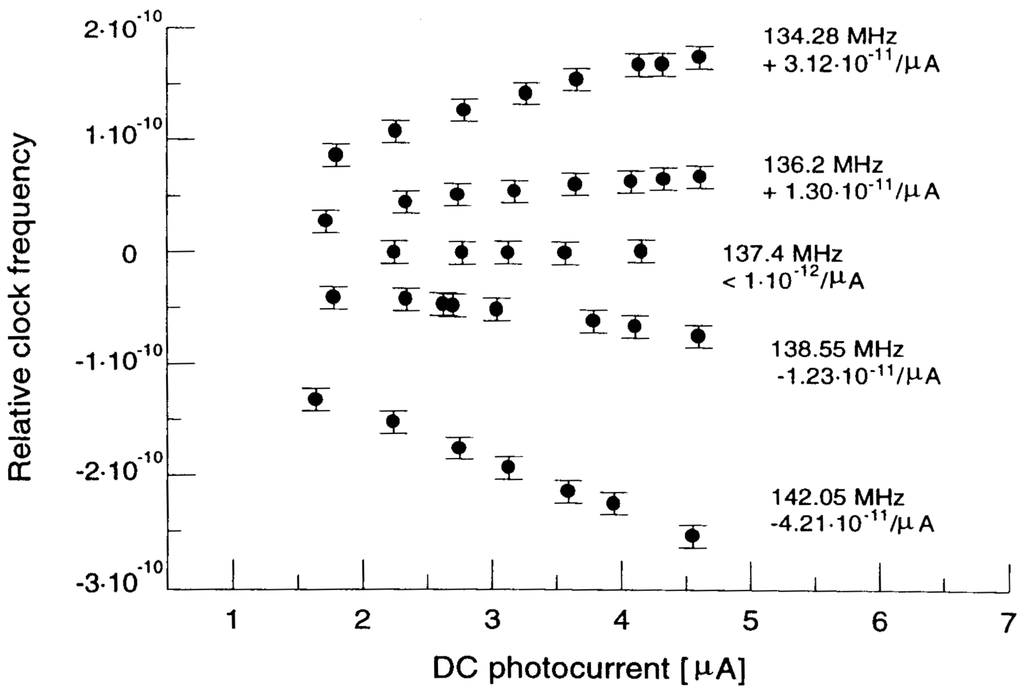

Figure 2 **Fine tuning of the laser frequency to the zero light-shift point.** *The clock transition frequency shift is plotted as a function of the light intensity (1 μA ≈ 4 μW/cm²) for different laser detunings. The beat frequency and the residual light shift is indicated for each curve.*

The requirement on the laser frequency *stability* for a *short term stability* of 10^{-13} (Table 2) is not too severe, and any locking system with a bandwidth higher than 10 kHz fulfills it. Reaching a stability of 10^{-14} will be much more difficult. The requirement on the laser frequency *stability* for good clock *long term stability* is more severe and is not achieved in our present setup.

The requirement on the *accuracy* of the laser frequency tuning to the zero light shift frequency indicates that a fine tuning of the laser frequency is necessary (with an AOM, by some offset locking system, or by fine tuning of the buffer gas, for example) if we want to allow 1% of change in the light intensity. Otherwise, active stabilization of the light intensity is necessary.

Another method for overcoming this requirement on accuracy of laser tuning is provided by the interesting shape of the D_1 transition. In fact, since the detuning between the exited state hyperfine sublevels is large (as compared to the Doppler broadening) two partially resolved Doppler absorption lines and light shift dispersion curves are visible (Fig. 1). In our setup, there is only one zero light shift frequency, but theoretical calculations have shown that at lower buffer gas pressures three zero light shift frequencies are present (Ref. 7). At the transition buffer gas pressure passing from three to one zero, there are two zeros. One of these zeros is a second order zero, which means that at this particular frequency the clock would be insensitive to intensity *and* frequency fluctuations.

The D_2 transition does not have the partially resolved lines and the light shift has a simple dispersion shape. Since there are more saturated transitions, lines closer to the zero light shift frequency can be found. In our particular setup, the closest line (of a separated evacuated cell) was only 20 MHz away from $\nu_{LS=0}$. It is possible that by adjusting the buffer gas pressure this residual detuning might be further reduced.

2.2 Limitations from the microwave interrogation

2.2.1 Noise on the photocurrent

In presence of optical pumping, the microwave field at resonance induces a reduction of the photocurrent. The total absorption of light due to the microwave constitutes the double resonance signal used for stabilizing the quartz oscillator. Unfortunately, it can also introduce additional noise on the photodetector. In our setup, the noise increases to 6 pA/√Hz when the microwave is present. This value is obtained when the microwave frequency is set exactly at resonance "clock" frequency (without modulation). It increases strongly on the side of the resonance, indicating that it is more likely due to PM noise than AM noise. Additional efforts will be needed to reduce this noise.

The theoretical limit of the clock stability is $6\cdot10^{-13}\ \tau^{-1/2}$. This estimation is obtained from the experimental resonance signal (discriminator slope ≈ 1 nA/Hz) and the noise level.

2.2.2 Microwave PM noise

Synthesizer PM noise at all the even harmonics of f_m (microwave modulation frequency) limits the stability of passive frequency standards (Ref. 8). We have measured the PM noise of our microwave synthesizer at 100 MHz by using the "three-cornered-hat cross-correlation technique" (Ref. 9) and have obtained the following values :

$$
\begin{aligned}
S_\Phi(f) &= 3.2\cdot10^{-14}\ \text{rad}^2/\text{Hz} && @\ 100\ \text{Hz} \\
S_\Phi(f) &= 2\cdot10^{-14}\ \text{rad}^2/\text{Hz} && @\ 300\ \text{Hz} \qquad (1)\\
S_\Phi(f) &= 1.2\cdot10^{-14}\ \text{rad}^2/\text{Hz} && @\ 600\ \text{Hz} \\
S_\Phi(f) &= 1\cdot10^{-14}\ \text{rad}^2/\text{Hz} && >600\ \text{Hz}
\end{aligned}
$$

According to the quasi-static model described in Ref. 8, with a modulation frequency of 300 Hz, the short term stability limit is $2.4\cdot10^{-13}\ \tau^{-1/2}$. This estimation is based on the 100 MHz PM noise measurement. The PM noise at 6.8347 GHz might be higher than expected from the multiplication chain.

3. FREQUENCY STABILITY MEASUREMENTS

We have measured the frequency stability of laser-pumped rubidium frequency standard with the different laser systems and the results are shown in Figure 3.

In each case, the stability is higher than the best reported stability of lamp pumped rubidium frequency standards ($5\cdot10^{-13}\cdot\tau^{-1/2} \le \sigma_y(\tau) \le 1.5\cdot10^{-12}\cdot\tau^{-1/2}$).

We also note that the D_2 transition gives better results than the D_1 transition. In fact, the three corresponding curves are below $1\cdot10^{-12}\ \tau^{-1/2}$ and represent the best reported performance of any rubidium passive frequency standards.

We have obtained better results with the EC laser than with the solitary and the DBR lasers. However, all the curves corresponding to the D_2 line are practically within the error-bar range. This remark is in agreement with the fact that the three laser systems all yield results close to the shot noise (2.1.1). Two important conclusions follow:

(1) The laser linewidth does not a limit clock stability for $\sigma_y(\tau) \ge 5\cdot10^{-13}\ \tau^{-1/2}$. In fact, there are more than two orders of magnitude difference between the spectral linewidth of extended cavity lasers and solitary lasers.
(2) We have reached the limit of short term stability allowed by the total photocurrent noise (6 pA/√Hz) and there is a potential factor of 5 improvement.

4. CONCLUSIONS

We have built a laser-pumped rubidium clock and demonstrated a short-term stability of $5 \cdot 10^{-13}\ \tau^{-1/2}$. The theoretical shot noise limit for this clock is $1 \cdot 10^{-13}\ \tau^{-1/2}$. One important limitation is the residual AM noise on the detection photocell, we are presently investigating the possibility of reducing it.

Our measurements on the laser frequency *accuracy* and *stability* clearly show that the residual medium and long term clock frequency fluctuations are due to laser frequency changes.

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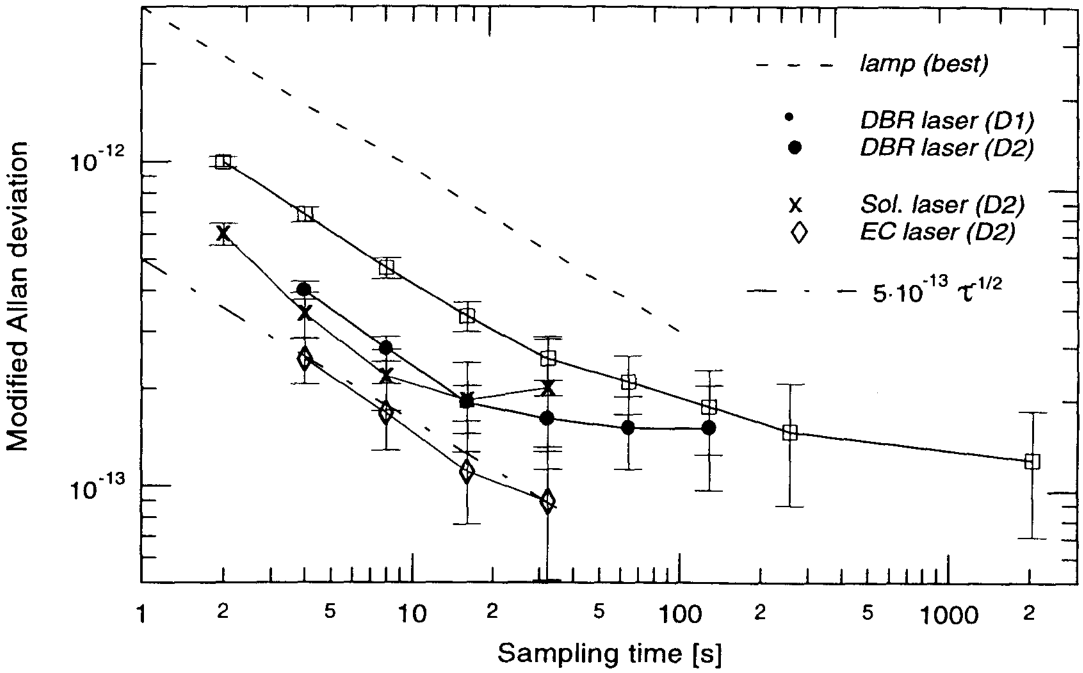

Figure 3 **Short-term stability**. *The experimental points correspond to the solitary (Sol.), extended cavity (EC) and DBR lasers. The corresponding atomic transitions (D_1 or D_2) of Rb^{87} are indicated. The best reported result with a lamp is shown for comparison.*

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