

## RECENT PROGRESS IN LASER-PUMPED RUBIDIUM GAS-CELL FREQUENCY STANDARDS

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### Abstract

This paper presents the current results of our development of a laser-pumped passive rubidium frequency standard. With a vapor cell containing isotopic  $\text{Rb}^{87}$  and a mixture of buffer gas we obtained a double resonance signal compatible with a short-term stability of  $2 \cdot 10^{-13} \tau^{-1/2}$  (shot noise limit). Measurements of the effect of the interrogating phase noise demonstrated that our microwave synthesizer did not limit this potential short-term stability. Two types of monochromatic light source lasers have been used: broad-band solitary lasers and extended cavity lasers. We found that their main limitation on the frequency stability was due to the AM noise detected by the photocell. In order to improve the S/N of the clock, an all-electronic AM noise cancellation technique has been successfully employed. Light-shift measurements allowed tuning the laser frequency to the zero light-shift point. Presently, our clock has a short-term stability of  $7 \cdot 10^{-13} \tau^{-1/2}$  ( $2 < \tau < 40$  s) with the solitary laser and  $5 \cdot 10^{-13} \tau^{-1/2}$  ( $4 < \tau < 40$  s) with the extended cavity laser. These are the best reported performances for passive rubidium clocks.

### 1. Introduction

The paper is organized in the following manner. This section introduces topics related to the short-term stability of laser-pumped rubidium clocks. The second section describes the different components of the clock, outlines the experimental setup, and illustrates the laser noise cancellation and the light-shift adjustment. The third section shows our experimental results of frequency stability measurements. A summary concludes the paper.

Laser-pumped, gas-cell, passive frequency standards have been the subject of many studies [1]. These studies focused not only on the development of a new type of atomic clock but also on the investigation of interesting physical effects, especially those related to the light-shift [2]. Three main directions are presently under investigation: (1) the replacement of the discharge-lamp rubidium clocks; (2) the possibility of new applications for greatly miniaturized clocks; (3) the development of a "super" local oscillator with a short-term stability at the  $10^{-14} \tau^{-1/2}$  level for use in clocks based on slow atoms and ions.

A detailed discussion of these different aspects is beyond the scope of this work. However, a short presentation of the principal ideas available in the past reports will simplify the discussion of our work towards the development of a super local oscillator. This short presentation is organized in two sections. The first section reviews the new physical processes which occur in the cell when a laser is used instead of the lamp. The second introduces our main field of interest: the improvement of the short-term stability.

### Understanding the new physics

The first microwave/optical double resonance experiments involving a laser-pumped vapor cell evidenced a new phenomenon [3] called the light-shift saturation, which was in apparent disagreement with well known physical laws [4]. Later, it was shown that this effect was caused by the light and microwave inhomogeneities in the interrogated vapor [5]. Finally, it was demonstrated that these effects were mainly due to the transverse inhomogeneities in the laser beam [6].

Light-shift saturation is related to another interesting phenomenon called the double resonance signal

saturation or peaking [7], which must be considered to optimize the clock parameters. Thanks to this more general point of view, the measured characteristics of the double resonance signal (width, amplitude and shift) can be related in a quantitative way to the theoretical predictions. Careful calculations realistically quantify the ultimate performance of the laser-pumped vapor gas-cell frequency standards at a level of  $1\text{-}2\cdot 10^{-13} \tau^{-1/2}$  ( $\tau$  is the sampling time), and relate these numbers to the magnitude of the physical quantities involved in the experiment [8].

However, the discrepancy between predicted and measured short-term stability is still not understood. In fact, the short-term frequency stability of the laser pumped clocks was in general not better than that of the best lamp-pumped rubidium clocks which, is now approximately  $2\cdot 10^{-12} \tau^{-1/2}$ . Explaining this discrepancy is one of our main objectives.

### Toward a super local oscillator

Two problems prevent us from reaching our desired short-term stability: the limitations due to the interaction of the atoms with the light field and those due to the interaction with the microwave field.

#### *a. Limitations due to the atom-light interaction*

The best short-term stability that can be obtain from a passive clock is determined by the ratio of the shot noise on the detection photocell ( $\sqrt{2\cdot q\cdot I}$  where  $I$  is the photocurrent and  $q$  is the charge of the electron) and the discriminator slope ( $D$ ), according to equation (1) [8].

$$\begin{aligned} \sigma_y(\tau)_{\text{shot-noise}} &= \frac{1}{\sqrt{2}} \sqrt{S_y(f_m)} \cdot \tau^{-1/2} \\ &= \frac{\sqrt{2\cdot q\cdot I}}{\sqrt{2\cdot D\cdot \nu_{Rb}}} \cdot \tau^{-1/2} \\ &\approx 1\cdot 10^{-10} \frac{\sqrt{2\cdot q\cdot I}}{D} \cdot \tau^{-1/2}, \end{aligned} \quad (1)$$

where  $S_y(f)$  is the spectral density of fractional frequency fluctuations,  $f_m$  is the modulation frequency, and  $\nu_{Rb}$  ( $\cong 6.8347$  GHz) is the atomic "clock transition". Typically, the shot noise limit in a lamp-pumped rubidium is  $1\text{-}2\cdot 10^{-12} \tau^{-1/2}$ . In fact,  $\sqrt{2\cdot q\cdot I} \cong 5 - 10$  pA/ $\sqrt{\text{Hz}}$ , and  $D \cong 0.4 - 0.8$  nA/Hz. Furthermore,

this estimation corresponds to the best measured stability in today's lamp-pumped rubidium clocks. Using a laser, with its more efficient optical pumping, the shot noise can be reduced to 1 pA/ $\sqrt{\text{Hz}}$ , and the discriminator slope increased by a factor 2 or 3. This should improve the short term stability by approximately one order of magnitude. With wall-coated cells, the discriminator slope can be increased by about a factor 15 so that the improvement could in principle be two orders of magnitude.

$$\sigma_y(\tau)_{\text{shot noise}}^{\text{laser-buffer gas}} \approx 1 - 2\cdot 10^{-13} \cdot \tau^{-1/2} \quad (2)$$

$$\sigma_y(\tau)_{\text{shot noise}}^{\text{laser-wall coating}} \approx 1 - 2\cdot 10^{-14} \cdot \tau^{-1/2}$$

However, these advances have never been achieved due to limitations other than shot noise. As far as the laser is concerned, these limitations are suspected to be related to the AM and FM noise, and the light shift experienced by the rubidium atoms.

#### *b. Limitations due to the atom-microwave interaction*

One important limitation to the short-term stability is related to the phase modulation (PM) noise in the 6.8347 GHz synthesizer. When examined in detail, the limit on short-term frequency stability depends on the modulation index, line width, and all even harmonics of  $f_m$  ( $P_i$  is the Fourier coefficient of rank  $i$  in the response of the resonance) [9]:

$$\sigma_y(\tau)_{\text{PM noise}} = \sqrt{\sum_{n=1}^{\infty} \left( \frac{P_{2n-1} - P_{2n+1}}{P_1} \right)^2 S_y(2nf_m)} \cdot \frac{\tau^{-1/2}}{2} \quad (3)$$

The largest contribution is due to the noise at  $\pm 2 f_m$  from the carrier (1st term) which can be written as a function of the spectral density of PM noise  $S_{\phi}(f)$ . The quasi-static model for the special case of square wave modulation predicts:

$$\sigma_y(\tau)_{\text{PM noise}} \approx \frac{2}{3} \cdot \frac{f_m}{\nu_0} \cdot \sqrt{S_{\phi}(2f_m)} \cdot \tau^{-1/2} \quad (4)$$

According to this formula, if we suppose a modulation frequency of 300 Hz (which is reasonable for a buffer gas-cell clock), the PM noise at 100 MHz has to be as low as  $1\cdot 10^{-14}$  rad<sup>2</sup>/Hz (at a Fourier frequency of 600 Hz) in order to obtain a short-term stability of  $2\cdot 10^{-13} \tau^{-1/2}$ .

However, the above formulas give only a first approximation on the actual limitation from the phase noise of the synthesizer since the other coefficients (4th, 6th, etc.) might play a role depending on the desired level of stability. Furthermore, these formulas are based on the so-called quasi-static approximation, which is valid only for low modulation frequencies and might not be strictly correct when the modulation frequency approaches the atomic line-width.

## 2. Experimental setup and preliminary measurements

This section presents the three main components of our clock: the physics package, the laser diode, and the microwave synthesizer. The overall experimental setup and some preliminary measurements are then discussed.

### The physics package

We used the physics package of an existing lamp-pumped rubidium frequency standard with the lamp and filter sections removed. The cylindrical absorption cell had a volume of 25 cm<sup>3</sup> and contained isotopic Rb<sup>87</sup> and a mixture of buffer gas which provides efficient quenching and a lower temperature coefficient. The microwave cavity used a TE<sub>011</sub> mode and had a quality factor of approximately 100. The detection photocell was removed and replaced by a lens so that an external photodetector could be used. Part of the original electronic breadboard was also employed to control the temperature of the absorption cell.

### The laser diodes

We used two types of laser diode sources, a broad-band solitary laser and an extended-cavity grating feedback laser. Both lasers were operated on the D<sub>2</sub> (5S<sub>1/2</sub> → 5P<sub>3/2</sub>, 780 nm) rubidium line. Their frequencies were servo-controlled to a saturated absorption feature in a separate evacuate Rb<sup>87</sup> cell. An acousto-optic modulator (AOM) was used to split the light in two beams having slightly different frequencies. These beams were sent to the saturated absorption cell and to the interrogated cell, respectively (see Figure 2). Thus, a fine optical frequency adjustment (0 < f < 50 MHz) was possible by changing the RF frequency injected on the AOM. The coarse tuning (50 < f < 500 MHz) could be done by choosing the appropriate Doppler-free line in the saturated absorption spectrum and the proper diffraction order from the AOM. The solitary laser and

the extended cavity laser had approximate line widths of 50 MHz and 100 kHz, respectively. We present hereafter the measurements of their direct intensity noise as well as the AM noise increase when an atomic absorption line is placed in the light path.

### The microwave synthesizer

We used a frequency synthesizer chain starting from a low PM noise 5 MHz local oscillator (the development of low-noise synthesizers at NIST has been described earlier [10]). The phase modulation was applied to the 10 MHz carrier in the frequency synthesizer chain. To reach our goal to improve the short-term stability, we focused on two areas : (1) reducing the PM noise out of the phase modulator, and (2) reducing the PM noise of the x20 multiplier from the 5 MHz quartz oscillator to 100 MHz signal. Following the design philosophy of Ferre-Pikal et al. [11], we significantly improved the PM noise of both PM modulator and the frequency multiplier. The present PM noise at 100 MHz is :

$$S_{\phi}(f) = 3.2 \cdot 10^{-14} \text{ rad}^2/\text{Hz} @ 100 \text{ Hz}$$

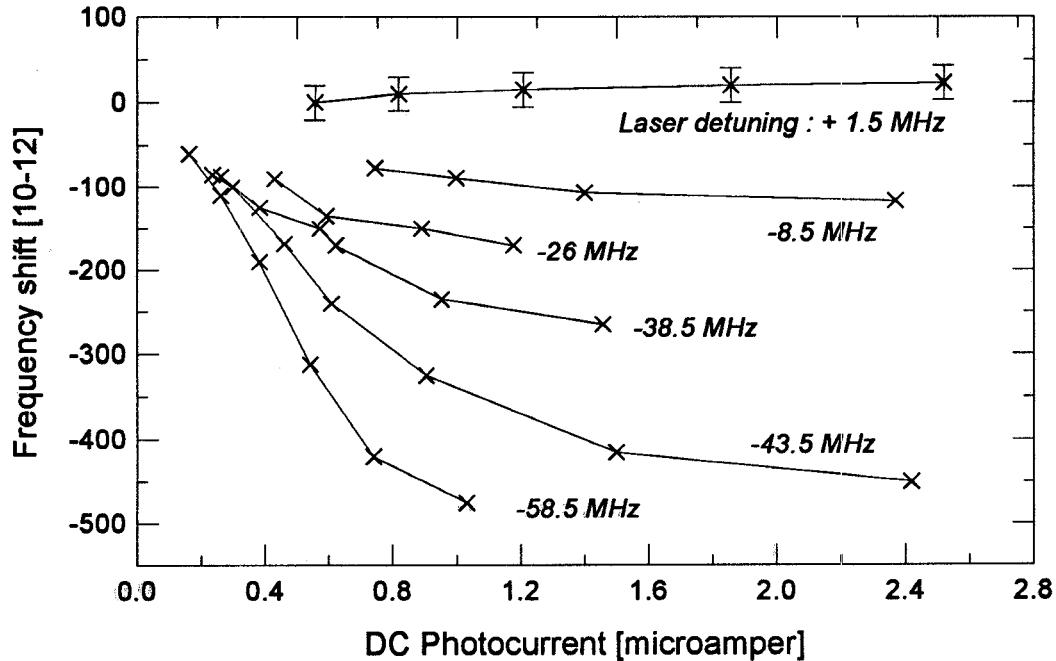
$$S_{\phi}(f) = 2 \cdot 10^{-14} \text{ rad}^2/\text{Hz} @ 300 \text{ Hz} \quad (5)$$

$$S_{\phi}(f) = 1.2 \cdot 10^{-14} \text{ rad}^2/\text{Hz} @ 600 \text{ Hz}$$

According to (4), this PM performance is compatible with a short-term stability below  $3 \cdot 10^{-13} \tau^{1/2}$ , for a modulation frequency between 100 and 400 Hz. Preliminary measurements indicates that the contributions of the 4th, 6th and 8th harmonics are small enough to be neglected this level.

### Laser frequency tuning to the zero light-shift point

It was not our intention to perform fundamental measurements of light-shift coefficients, but only to set the laser frequency at the most convenient point so that light-shift effects on the short-term and long-term stability of the clock were as small as possible. As described previously, light-shifts have to be measured in a very accurate way since saturation effects can occur and lead to incorrect conclusions. We chose to tune the laser to one of the Doppler-free transitions at 780 nm starting from the F = 2 hyperfine level of the ground state of Rb<sup>87</sup>, since the optical pumping is more efficient than when the F = 1 level is depopulated. Figure 1 shows an example of the results of our laser frequency fine tuning measurements.



**Figure 1.** 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 for different laser detunings with respect to the zero light-shift frequency.

The above figure shows that it is possible to tune the laser frequency so that the light-shift is zero within the uncertainty of our measurements. We also see that a saturation phenomenon occurs for a photocurrent above 1  $\mu\text{A}$ . This result reveals the effect of residual inhomogeneities in the interaction between the rubidium atoms and the two microwave and optical radiation fields. As a result of this technique, we could reduce the light-shift coefficient below  $1 \cdot 10^{-13}$  /(% of light intensity). For this particular atomic transition, we found an average value of the light shift coefficient which confirmed both previous theoretical and experimental values :  $|\Delta\nu_{\mu\text{-wave}} / (\Delta\nu_{\text{Laser}} \cdot I_{\text{transmitted}})| \cong 2 \text{ kHz}/(\text{GHz} \cdot (\mu\text{W}/\text{mm}^2))$  [12].

#### Laser noise measurements and noise cancellation

As mentioned previously, an important limit for the short-term stability of the clock is the noise level on the photodetector, and the ultimate goal is to reach the shot noise limit of approximately 1  $\text{pA}/\sqrt{\text{Hz}}$ . The measured intensity noise in operating conditions was 4  $\text{pA}/\sqrt{\text{Hz}}$

(Relative Intensity Noise  $RIN = 3 \cdot 10^{-13}/\text{Hz}$ ) for both the solitary laser and the extended cavity laser.

This AM noise increased when the rubidium cell was placed in the path of the laser beam, and its level depended on the laser detuning in the absorption line, as well as on the temperature of the vapor. In typical conditions and at the zero light-shift frequency, we measured 32  $\text{pA}/\sqrt{\text{Hz}}$ . This value did not vary significantly within the tuning range of the RF signal on the AOM ( $\sim 50 \text{ MHz}$ ). This additional noise was suspected to be the result of a conversion through the atomic absorption line of the laser FM noise into AM noise [13]. However, the fact that the noise level was similar for the two types of lasers seems to contradict this interpretation. One possible explanation might be the fact that our present extended cavity laser is very sensitive to mechanical vibrations which results in additional FM noise.

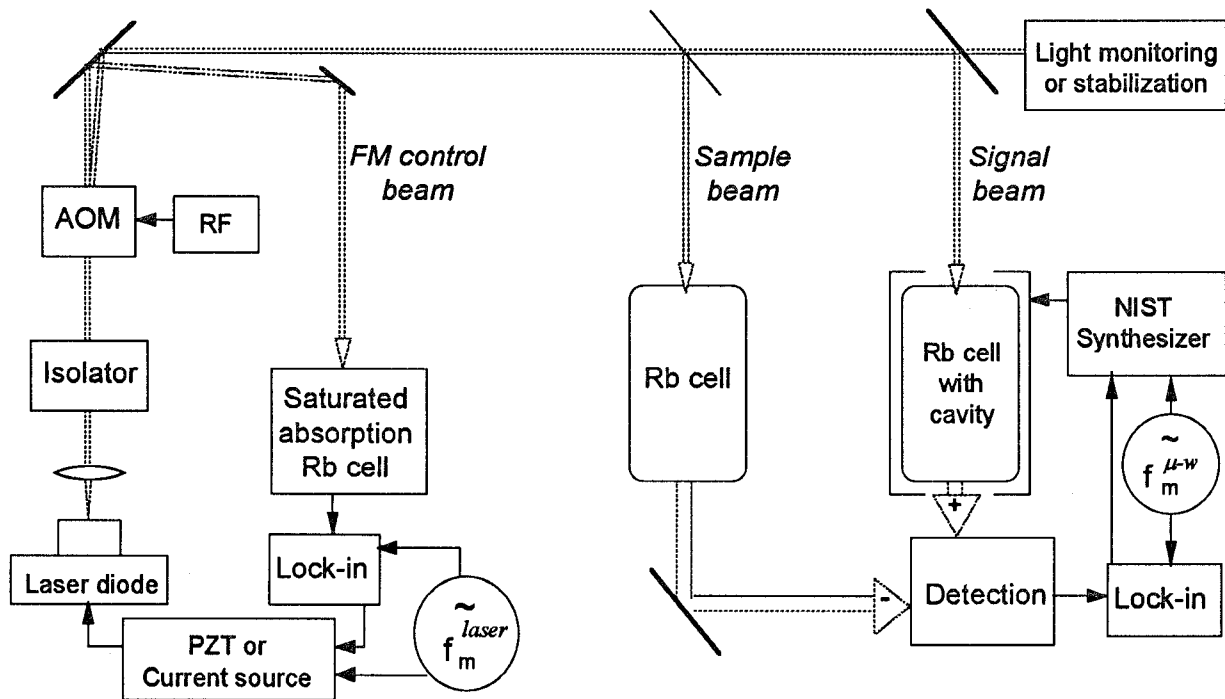
As a first attempt to reduce this noise, we tried to optimize the parameters of the laser frequency locking. With the solitary laser, for example, the modulation

frequency of the current was increased to 70 kHz in order to increase the bandwidth of the locking system. However, this did not significantly improve our results.

After failing to actively reduce the intrinsic AM and FM noise in the laser beam, we decided to cancel it from the detection signal in a passive way. The pumping beam was separated into two beams with a beam splitter and the additional beam was used as a sample beam in a classical photocurrent subtraction scheme which cancels the AM noise out of the first amplifier of the detection system [14]. A second rubidium cell, identical to the absorption cell, was

placed in the path of this beam for canceling the FM contribution to the AM noise. Figure 2 displays the overall experimental setup. As a result the total AM noise out of the detector was 3 pA/ $\sqrt{\text{Hz}}$  (without rubidium cells in the path the shot noise level is reached), which was satisfactory as a first step.

As it is shown on Figure 2, a detector is placed to monitor the level of the light intensity incident on the rubidium cell. This detector can also be used for maintaining this intensity constant by automatically adjusting the RF power on the AOM.

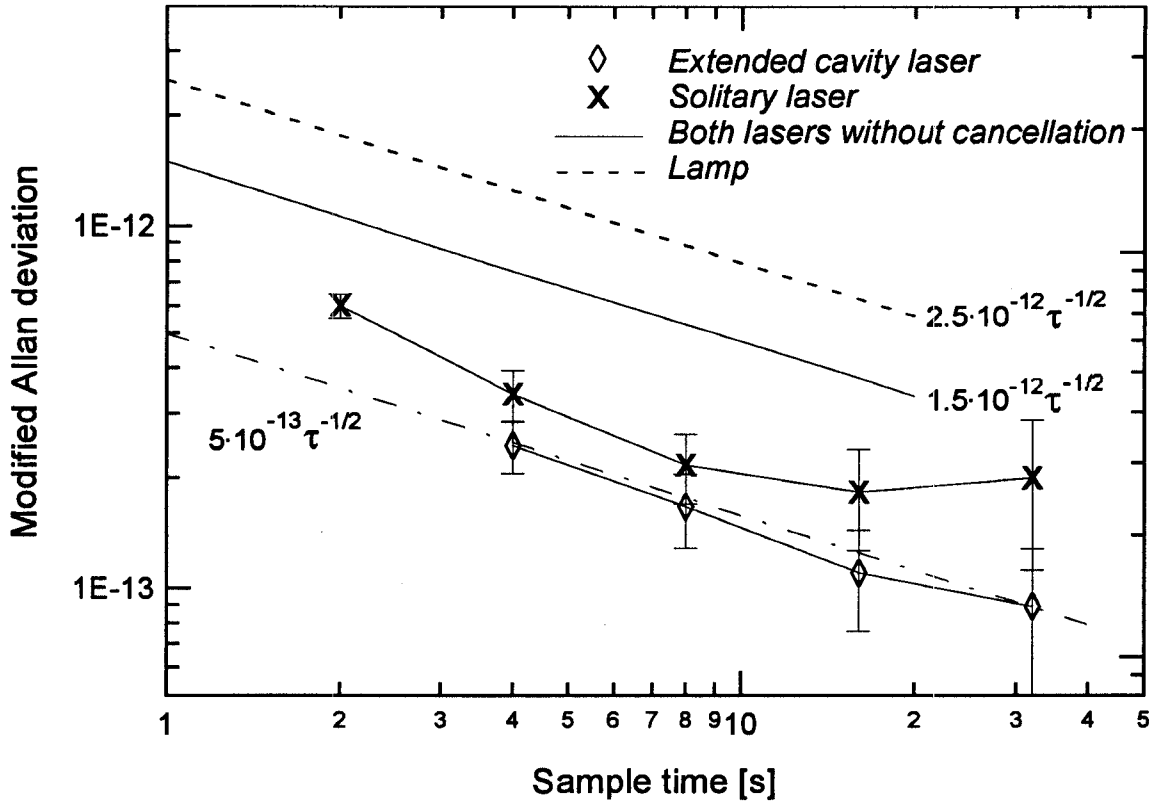


**Figure 2.** Experimental setup. An acousto-optic modulator allows fine tuning of the laser frequency. The sample beam cancels AM and FM noise.

### 3. Frequency stability measurements

Figure 3 shows the frequency stability obtained with the experimental setup described above, as well as the performance reached without noise cancellation. This picture demonstrates clearly the limitation resulting from the laser AM and FM noise. Furthermore, since

we have observed that no significant improvement is achieved with the noise cancellation if no rubidium cell is placed in the path of the sample beam, we can conclude that the main contribution to the AM noise results from the presence of the absorption line in the path of the laser beam.



**Figure 3. Short-term stability.** The experimental points correspond to the solitary and extended cavity lasers. Typical results obtained with a lamp or lasers without noise cancellation are shown for comparison.

These results are very important, since it is the first time that a rubidium clock has demonstrated a short-term stability better than  $1 \cdot 10^{-12} \tau^{-1/2}$ , and  $1 \cdot 10^{-13}$  after less than 30 s. However, since the shot noise limit has not yet been reached, it is worthwhile to try to understand and reduce the laser AM and FM noise. Potentially, this might improve the short-term stability of the clock by approximately a factor of 3. Furthermore, the effect of the microwave radiation on the noise level at the photodetector has not been studied in details but might also affect the clock stability in a significant way.

Remarks on the medium and long term stability

Unfortunately, the results for longer sample times ( $\tau > 40$  s) depend on the environmental fluctuations. Typically, the Allan deviation starts to increase after 40 s and is approximately  $8 \cdot 10^{-13}$  at 1000 s. We are presently investigating the reasons of this high

sensitivity to environmental conditions. We suspect microwave power changes and RF power fluctuations (on the AOM). We are also investigating possible laser changes due to aging processes and temperature sensitivity.

**4. Summary**

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 is  $2 \cdot 10^{-13} \tau^{-1/2}$ . Our results show that the main limitation results from the AM noise on the detection photocell, increased by the transmission through the absorption cell. The origin of this additional AM noise is still not fully understood since it does not change when going from the solitary to the extended cavity laser. At the present stability level, the light-shift does not limit the short-term stability. We also have studied the effect of synthesizer

interrogation PM noise on the clock stability. These results indicate that the PM noise in our synthesizer contributes less than  $2 \cdot 3 \cdot 10^{-13} \tau^{-1/2}$  to the fractional instability.

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