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Intensity detection noise in pulsed vapor cell frequency standards

Claudio E. Calosso, Michele Gozzelino, Aldo Godone, Haixiao Lin, Filippo Levi and Salvatore Micalizio

Laser intensity noise is currently recognized as one of the main factors limiting the short-term stability of vapor-cell clocks.

In this paper, we propose a signal theory approach to estimate the contribution of the laser intensity fluctuations to the short-term stability of vapor-cell clocks working in pulsed regime. Specifically, given a laser intensity noise spectrum, an analytical expression is derived to evaluate its impact onto the clock Allan deviation.

The theory turns out in good agreement with the experimental results obtained with a prototype of pulsed optically pumped (POP) Rb cell clock and can be extended to other compact clocks.

I. INTRODUCTION

Laser pumped vapor-cell clocks have recently achieved very good results in terms of frequency stability [1–6], reaching the 10^{-13} level for integration times τ of one second.

In the long term period, the best performances have been demonstrated operating the clock in pulsed regime. In this regard, two approaches have been successfully proved: the pulsed optical pumping (POP) and the pulsed coherent population trapping (CPT) techniques. In the first one, the atoms, after being optically pumped by a strong laser pulse, experience a couple of microwave pulses according to the Ramsey interrogation scheme. After that, a weak laser pulse is used to detect the atoms that have made the clock transition [7].

In the pulsed CPT, the atomic sample experiences a two-color laser pulse (Λ pulse) which prepares the atoms in the so called dark state. Then the atoms freely evolve for a time limited by the relaxation phenomena taking place inside the cell. Finally, a second Λ pulse probes the phase of the dark state. This scheme allows the detection of the so called Raman-Ramsey interference fringes [8–10].

In both approaches, the clock transition is commonly detected in the optical domain by monitoring the absorption profile of a probe laser after the passage through the cell. Laser amplitude noise is thus directly added to the error signal, degrading the clock performances via laser amplitude modulation to amplitude modulation (AM-AM) transfer [11].

Indeed, since other stability contributions (e.g. shot-noise and Dick-effect from the local oscillator) are kept in the low 10^{-14} [12], laser amplitude fluctuations, usually expressed in terms of relative intensity noise (RIN), may play an important role to limit the short-term stability of most of the state-of-the-art prototypes.

Despite the importance of this topic, the laser detection noise has been considered in the literature only in few works [13,14] and often with ad hoc approximations. Some studies are reported in [15] and in [16] assuming since the beginning a white noise contribution to the clock final stability. This assumption is not always valid, especially in pulsed operation which involves clock cycle frequencies in the range 100 and 200 Hz (and relative multiples) where lasers have in general a flicker behavior.

Here we report a signal theory based approach leading to a more general evaluation of the laser RIN impact on the clock stability. Besides providing an analytical expression, the results of this work can be useful to impose precise constraints on the laser source needed to reach a given stability target.

The paper is organized as follows: in Section II we develop the theory, both in time and frequency domains. The proposed model aims to calculate the contribution to the stability $\sigma_y(\tau)$ for a clock in pulsed operation, given the laser relative intensity noise (RIN) expressed in terms of power spectral density. Specifically, two situations commonly found in the experiments will be discussed: laser RIN affected by white frequency noise and by flicker noise. Section III describes the experiments performed with a prototype of POP Rb clock. Conclusions are reported in Section IV.

II. THEORY

We consider the experimental set-up depicted in Fig. 1 which can be adjusted to describe, for example, either a prototype of POP clock or a pulsed CPT clock. We are not interested to the details of the experimental apparatus (for example, in the case of pulsed CPT and electro-optic modulator, not shown in the figure, would be required).

The important issue in this context is that the laser signal at the input of the cell used to detect the clock transition is affected by intensity noise that will impact on the clock frequency. To evaluate this instability contribution, we take into account that the clock operation requires a sequence of steps, like construction of the error signal, sampling, etc.. well represented by input/output connections of functional blocks, typical of the signal theory [17]. The purpose of this section is then to provide the mathematical framework to describe how the optical detection signal is processed when a clock works in pulsed regime and how the laser intensity noise is transferred to the clock frequency.

A. Time domain analysis

With reference to Fig. 1, the laser intensity $I(t)$ impinging on the photodiode includes an average term I_0 and a random

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C. Sampling every clock cycle

A different locking protocol can be adopted. Specifically, we can apply the correction to the local oscillator every clock cycle T_c , by using every new clock acquisition together with the previous one, already available. In this way, together with the difference between the left and the right side of the resonance at $t = 2kT_c$, we have also the difference between the right and the left side for $t = (2k+1)T_c$, that has opposite sign. With respect to Eq. (4), this impacts on the sampled error signal, now available at time kT_c , as:

$$e_\delta(t) = e(t) \times T_c \sum_{k=-\infty}^{\infty} \cos\left(\pi \frac{t}{T_c}\right) \delta(t - kT_c) \quad (13)$$

where it appears the additional demodulation factor $\cos\left(\pi \frac{t}{T_c}\right)$ that compensates for the change of sign between odd and even cycles.

The equivalent block diagram is shown in Fig. 4.

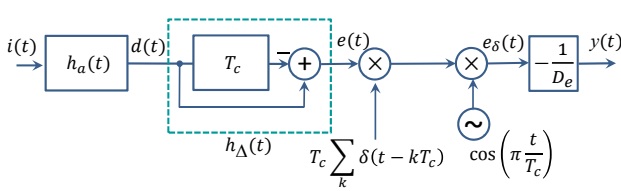


Figure 4. Signal theory block scheme for sampling the clock signal every T_c .

The analysis in the Fourier domain now leads to

$$S_{e_\delta}(f) \simeq 2[1 + \cos(2\pi f T_c)] \sum_{k \text{ odd}} \left| H_a\left(\frac{k}{2T_c}\right) \right|^2 S_i\left(\frac{k}{2T_c}\right) \quad (14)$$

Since the degradation of the short-term stability is due to aliasing, we could expect an improvement when the sampling rate is doubled. In fact this is not the case, because (14) coincides to (8) for $f \rightarrow 0$. This protocol gives no significant advantages, at least for long averaging times ($\tau \gg 2T_c$).

III. EXPERIMENTS

The theory has been verified for the POP clock. The experimental setup is thoroughly described in [1]. Here we just recap the interrogation protocol and the experimental parameters which are of interest for the model validation.

The timing sequence is composed of an optical pumping pulse (0.4 ms), followed by a Ramsey sequence (3.8 ms) and finally an optical window is enabled to detect the clock transition (0.15 ms). The total cycle time, including short pauses between the different steps, is 4.39 ms. The pumping pulse power is 16 mW, whereas the detection probe power is 100 μ W. The Ramsey fringes obtained in this conditions show a contrast of 27.8% (see Fig. 3) and an atomic quality factor Q_a of 4.3×10^7 . In clock operation, the correction on the LO frequency is performed every two cycles (i.e. every 8.78 ms), thus following the protocol described in sections II A and II B.

In order to validate the model, the RIN has been artificially degraded by modulating the amplitude of the RF signal that drives the AOM. The amount of noise we injected is such that all other contributions to the short-term stability are completely negligible. In this particular condition, we can directly compare the measured clock stability to the stability predicted by the model given the measured laser intensity noise. We considered two common cases encountered experimentally: white and flicker noise. In Fig. 5 the noise levels, as measured before the clock cell, are shown. We measured a white noise level h_0^i of $1.7 \times 10^{-7} \text{ Hz}^{-1}$ band-limited to 25 kHz and a flicker level h_{-1}^i of 4.8×10^{-6} , respectively. In Fig. 6 the

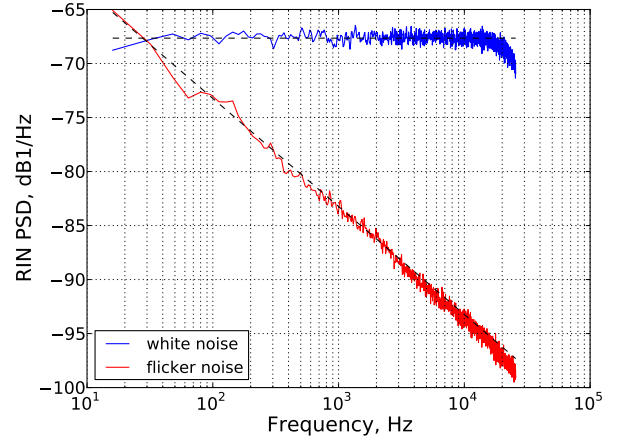


Figure 5. AM noise levels used in the model validation as measured at the input of the clock cell.

measured clock stability for the two cases is shown.

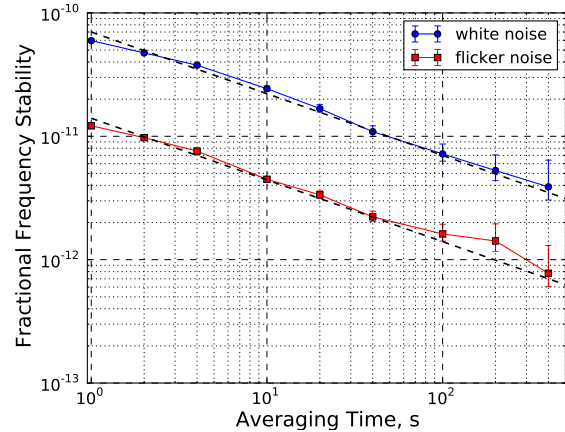


Figure 6. Measured clock ADEV for the two cases considered in the text: laser RIN affected by white noise and by flicker noise.

In Table I we compare the measured stabilities to the results obtained with the model. Specifically, the Allan deviations for the two cases of white and flicker noises are estimated with Eq. (9) using as input the noise levels and the clock parameters (C , τ_d , T_c , T). In the two cases, also the approximate results of Eqs. (11) and (12) are reported. The results are consistent with the measured stability within 10%.

Table I
STABILITY MEASUREMENTS COMPARED TO THE ESTIMATE FROM THE MODEL

Input noise	Measured ADEV(1 s)	Estimated ADEV(1 s)	ADEV(1 s) from Eqs. (11) and (12)
White noise ($1.7 \times 10^{-7} \text{ Hz}^{-1}$)	7.0×10^{-11}	6.4×10^{-11}	6.3×10^{-11}
Flicker noise ($4 \times 10^{-6}/f$)	1.4×10^{-11}	1.2×10^{-11}	1.2×10^{-11}

IV. CONCLUSION

In this paper we have analyzed how the laser intensity noise affects the short-term stability of a clock working in pulsed operation. Specifically, we developed a signal-theory model which accounts for all the operations required to lock the LO to the optically detected signal, including construction of the error signal and sampling. Given an arbitrary intensity noise spectrum of a free running laser, the model predicts the power spectral density of the clock error signal, and the corresponding contribution to the clock short term stability, once the shape of the resonance has been specified. In this regard, the paper results can be greatly useful in the clock design phase: for instance, by considering the laser RIN reported by the manufacturer and the expected clock signal parameters (contrast, quality factor, etc.), it is immediate through Eqs. (11) and (12) to give an estimate of the RIN contribution to the clock Allan deviation.

Also, the model gives more insight into the origin of the noise transfer, which is basically an aliasing process, as in the Dick-effect case. However, differently from the Dick effect, the Fourier frequencies of interest in the aliasing process are the odd multiples of $f_c/2$, due to the periodicity of the lock-in transfer function ($H_\Delta = 4 \sin^2(\pi f T_c)$). This is in agreement with the intuitive reasoning that a sinusoidal noise does not interfere with the lock-in as long as its periodicity is equal to an even multiple of the lock-in differentiating cycle time ($2T_c$ corresponding to $f_c/2$).

The theory is absolutely general and can be easily extended to pulsed CPT vapor cell standards and also to other devices where the laser intensity noise is expected to play a role in affecting the frequency stability, like in compact cold atom clocks [22–24].

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