Atomic clock using coherent population trapping in a cesium cell: frequency stability and limitations

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Abstract. Toward the next generation of compact devices, atomic clocks based on coherent population trapping (CPT) offer a very interesting alternative. We present a review of our studies on the short and mid term stability of a compact high performance atomic clock based on CPT in view of portable applications.

1. Introduction

Compact and high stability clocks are needed in many on-board applications like for example global navigation satellite system (GNSS). The present stability of vapor cell atomic clocks used in Galileo program are $5 \times 10^{-12}$ at 1 s [1]. A number of innovative schemes for compact clock based on the double-resonance technique [5], pulsed optical pumping and microwave interrogation [6, 7], or coherent population trapping [2, 3], are showing performances at the level of hydrogen maser. The project presented here describes a compact atomic clock laboratory prototype which uses an original atoms interrogation technique called coherent population trapping (CPT)[8]. Contrary to the double resonance clock used today for GPS, the microwave pulses are optically carried. This allows the suppression of the microwave cavity and leads to a high miniaturization potential. In this paper, we present the implementation and the metrological characterization of a CPT clock prototype developed at LNE-SYRTE. Our prototype intends to explore what would be the ultimate stability of a CPT based device. To this aim, we combine a high signal amplitude and narrow resonance width by using a so-called double-Λ scheme and Ramsey interrogation technique [9, 10]. The reported metrological characterization includes some technical solutions for the effects that limit the frequency stability of our clock, such as the Dick effect and the laser amplitude noise.

2. Experimental setup

The experimental setup of the clock is shown in Figure 1. In order to pump the atoms in the clock dark state (linear superposition of $|F = 3, m_F = 0 \rangle$ and $|F = 4, m_F = 0 \rangle$) we use two phase-locked external cavity diode lasers tuned to the Cs D1 line at 894 nm. The master laser (M) is frequency locked to the $(F = 4 - F' = 4)$ transition via saturated absorption in an auxiliary evacuated Cs cell. The scheme contains a frequency modulated acousto-optic modulator (AOM), in order to avoid modulating the master laser frequency. It also allows
shifting the laser frequency compared to the Cs reference for compensating the buffer gas shift
in the clock cell. The slave laser (S) is phase locked to the master laser with a frequency offset
tunable near 9.192 GHz, i.e. around the \((F = 3 - F' = 4)\) transition, by comparison with a
low-noise synthesized microwave signal. The frequency synthesizer is built as follows. A 100
MHz Rakon quartz oscillator (LO) is phase locked to the 100 MHz signal generated by a H-maser
of the laboratory. The LO signal is frequency multiplied to produce a 9400 MHz signal. The
last one is mixed with a 9.392 GHz signal issued from dielectric resonator oscillator (DRO). The
beat-note signal of 7.368 MHz is low pass filtered, amplified, and compared to a 7.368 MHz
signal delivered by a direct digital synthesizer. The resulting error signal is then used to lock
the DRO through a second-order loop whose bandwidth is about 180 kHz.

The two superposed laser beams are switched on and off by an AOM before travelling across
the Cs cell. The transmitted power is recorded by a low noise Si photodiode (PD). The resulting
digitalized signal is processed by the computer (PC) which drives the 7.4 MHz synthesizer as
well as the AOM switch. A digital loop is used in order to lock the synthesizer frequency. To
do so, the interrogation frequency (IF) hold at resonance, and the phase of the synthesizer is
square-wave modulated of \(\pm \pi/2\) during the period in the dark. The error signal is computed by
the PC which can lock the LO frequency or equivalently the synthesizer frequency. Its frequency
is proportional to the frequency difference between the maser and the Cs clock and the Allan
variance is computed from its record.

![Figure 1: Scheme of the experimental setup; The master laser (M) is frequency locked on Cs
resonance by a saturated absorption scheme (SA). The slave laser (S) is phase-locked on the
master laser. PBS polarization beam splitter, PLL phase-lock loop. The inset shows the involved
Cs energy levels.](image)

The Cs cell, 5 cm long and 2 cm diameter, is filled with a 20 torr \(N_2 - Ar\) buffer gas mixture
\((P(Ar)/P(N_2) = 0.4)\) [11]. The cell is temperature stabilized around 29°C which is the lowest
temperature sensitivity point. It is located inside a solenoid and surrounded by two magnetic
shields. A coaxial nonmagnetic wire is used with a homemade modified diode laser current source
for heating the cell. Since the temperature fluctuations can be transferred to the clock transition
frequency through the atomic collisions, the cell is temperature controlled within 100 \(\mu K\) which
limits the temperature effect at the level of few \(10^{-15}\).

3. Short term limitations and optimization
As mentioned in the introduction, narrow linewidth can be obtained by combining coherent
population trapping and Ramsey interrogation technique. The CPT clock operation
continuously repeats the following phases (see Figure 2 (a) bottom): a first pulse pumps the atoms in the dark state, which is a steady-state. The detection window is at the beginning of the next pulse. The laser pulse duration is typically 2 ms for our setup separated by a Ramsey time $T_R$ of 4 ms. $\tau_d$ typically around 10 $\mu s$ is the delay time after which the clock transition is observed through the transmission signal. The observed signal is averaged during a time $\tau_m$ typically 25 $\mu s$. The experimental Ramsey fringes are shown in Figure 2(a).

The Figure 2 (b) shows the CPT clock stability when the local oscillator (LO) is locked to the central fringe of the Ramsey fringes. In order to have a better understanding of the effects leading to this performance, in the following part we will describe the models, measurements and technical choices used to get a total contribution of those noise sources to the short term stability around $3 \times 10^{-13}$ at 1 s.

![Figure 2](image.png)

Figure 2: (a) Top: Ramsey fringes. $S_n$ and $S_{n+1}$ are the signal values measured on each side of the central fringe used to calculate the error signal. $\Delta \nu = 125$ Hz, SNR $= 42000$ in 1 Hz, $T_c = 6$ ms. Bottom: Time sequence of a CPT Ramsey clock (not to scale). $\tau_L$ is the length of each laser pulse, $T_R$ is the free evolution time. The signal is detected after a time $\tau_d$ at the beginning of each pulse, and averaged during a time $\tau_m$. (b) CPT clock frequency stability: In blue the calculated Dick effect, in green the estimated RIN contribution. The red curve represent the measured stability. The shot noise limit at 1 s is at the level of $2 \times 10^{-14}$.

3.1. Short term limitations

Assuming the frequency stability to be limited by two dominant noise sources, the relative laser intensity noise (RIN) and LO noise, the Allan variance can be written:

$$\sigma^2(\tau) = \sigma^2_{\text{Dick}}(\tau) + \sigma^2_{\text{SNR}}(\tau)$$

(1)

with $\sigma^2_{\text{Dick}}(\tau)$ the contribution of the local oscillator phase noise and $\sigma^2_{\text{SNR}}(\tau)$ the contribution of the signal-to-noise ratio. The Dick effect is due to the down-conversion of the local oscillator intrinsic frequency noise at Fourier frequencies higher than the interrogation frequency [12]. The noise contribution to the Dick effect of each component of the microwave chain has been evaluated [13]. It turned out that the optical phase lock loop (PLL) noise gives the main contribution, evaluated at the $2.1 \times 10^{-13}$ level. The total Dick limited stability is estimated at the level of $2.7 \times 10^{-13}\tau^{-1/2}$. In order to reduce this effect, current work is in progress to redesign our PLL and increase the bandwidth of our lock.
As already mentioned, the signal-to-noise ratio contribution due to the laser intensity noise is also an important effect. Using an intensity stabilization system, its contribution can be lowered until $1.7 \times 10^{-13}$ at 1 s. A second way to reduce the RIN contribution is, based on the idea that if the intensity noise dominates the noise budget, the fluctuations on the detected signal might be proportional to the intensity fluctuations before the cell. This has been successfully checked on our setup. Such system is already implemented on other compact clock setups [17]. The stability presented here has been measured without the normalization scheme, giving a good hope for improvement.

3.2. Optimization

In this section we present the optimization of the two main limiting effects on the short term stability. The optimization parameters are the detection time $\tau_m$ and the free evolution time $T_R$. We have shown previously [13] that both Dick effect and laser intensity noise decrease by increasing $\tau_m$. Therefore it seems that the clock frequency performances would be improved for longer detection times. However, our detection is destructive because the atomic phase originating the detected signal is progressively destroyed all along the laser detection pulse. The more $\tau_m$ increases, the more the fringe amplitude reduces and the instability of the clock increases. A similar study have been done on $T_R$. Indeed when $T_R$ increases, the signal decreases because of the atomic coherence relaxation.

The figure 3 (a) presents the evolution of the SNR contribution to the frequency stability as a function of $T_R$ and $\tau_m$. The best compromise is for $T_R = 3$ ms and $\tau_m = 150$ $\mu$s. The gain from the current time sequence parameters ($T_R = 4$ ms and $\tau_m = 25$ $\mu$s) is about 30% on the current SNR. The Dick effect decreases as $T_R^{-1/2}$ and as $\tau_m^{-1/4}$ [13]. The increase of the evolution time $T_R$ allows to improve the duty cycle. In this case the servo-loop of the LO adds less noise and the Dick effect decreases. Increasing $\tau_m$ allows to apply a temporal filter that reduces the influence of Fourier high frequency (Figure 3 (b)).

Figure 3: Influence of the free evolution time $T_R$ and detection duration $\tau_m$. (a) Contribution of the SNR to the frequency stability $\sigma(1s) \times 10^{13}$. The gain from current time sequence parameters $(T_R = 4$ ms, $\tau_m = 25$ $\mu$s) to $(T_R = 3$ ms, $\tau_m = 150$ $\mu$s) is around 30% on the current SNR. (b) Contribution of the Dick effect to the frequency stability $\sigma(1s) \times 10^{13}$. 
4. Laser intensity effects

The effect of the laser light is known as one of the major effects limiting the mid term stability of a CPT based clock [15, 16, 14]. Presently our setup shows a mid term stability at the level of $2 - 3 \times 10^{-14}$ for an averaging time of about 4000 s [14]. The main sources of degradation at mid term are the sensitivity of the clock transition to the temperature, magnetic field and laser intensity. The temperature sensitivity of the clock transition can be greatly reduced by a proper choice of the composition of the mixture of gases [11]. For our clock, the shift is limited to the $10^{-14}$ level for 1 mK temperature variation [14].

Due to the double-Λ excitation scheme, the resonance ($m = -1 - m = +1$) between neighboring Zeeman sublevels of the clock transition leads to a shift of the locked frequency. The power sensitivity of the clock transition in the double-Λ scheme has been measured as a function of the magnetic field. Our clock operates at the magnetic field which maximizes the amplitude of the clock signal, i.e. $B = 22 \mu$T. The bottom part of Figure 4 (a) shows the frequency shift due to each laser intensity as a function of the magnetic field. A zero sensitivity point is shown around $B = 8 \mu$T. Unfortunately, operating the clock at this magnetic field value reduces the amplitude signal by 10% (Figure 4 (a) Top). The effect of such a reduction on the signal amplitude on the short term stability is under evaluation.

Figure 4 (b) presents the combined contribution of the power laser and magnetic field effects on the total instability of the clock. By operating the clock at $B = 8 \mu$T (green curve), the limitation of the power shift can be reduced to the level of $5 \times 10^{-15}$ at 2000 s.

![Figure 4](image)

Figure 4: (a) Top: CPT signal amplitude as a function of the magnetic field. Bottom: Laser intensity shift as a function of the magnetic field (Red master laser, blue slave laser). (b) Contribution of the power shift effect on the instability of the clock. Red: $B = 22 \mu$T, green: $B = 8 \mu$T. Black measured frequency stability. By operating the clock with $B = 8 \mu$T, the limitation of the power shift can be reduced to the level of $5 \times 10^{-15}$ at 2000 s.

5. Conclusions

In summary we have presented a pulsed CPT vapor cell clock prototype. The studies of two main frequency limitations on the short term stability are reported: laser intensity noise and LO noise. The short term stability is at the present time around $3.2 \times 10^{-13}$ level at 1 s. This stability can be improved by optimizing the time sequence of the clock. The laser intensity noise can be further reduced by combining the intensity stabilization system with the normalization
scheme. The mid term stability is still limited after 200 s integration around $2 - 3 \times 10^{-14}$. The neighboring transitions impact the resonance frequency. This effect varies with the magnetic field value. A low sensitivity point has been shown. Using this value to operate the clock could lead to a drastic reduction of the power sensitivity of the clock. Experimental studies are carried in order to confirm this behavior.

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