Study of coherent population trapping occurring in ^{87}Rb atoms contained in wall-coated cells

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***Abstract*— We report on the continuous CPT-interrogation of ^{87}Rb atoms contained in a paraffin wall-coated cell. Based on the signal-to-noise measurements we predict a short-term stability better than 10^{-12} $\tau^{-1/2}$. This result confirms the interest on wall-coated cells for applications in high performance and compact vapor cell atomic clocks. We also report on our results on the influence of the cell temperature in the clock signal which has not be studied in this specific case as far as we know.**

I. INTRODUCTION

Since several years, the development of microwave atomic frequency standards that combine low dimensions and low consumption with good frequency stability performance has motivated many relevant works [1]. These devices find application in navigation, telecommunication, space exploration, defense industry and metrology.

Two kinds of resonances are typically used for the realization of compact standards: the optical microwave double resonance and the coherent population trapping resonance. The study of these resonances for clock applications is often performed in sealed cells filled with the alkali atoms and a buffer gas to reduce the alkali-atoms relaxation due to the atom-wall collisions. However, there is a second technique to reduce the relaxation of the atomic polarization in a cell. This technique is based on the use of chemically inert substances for coating the cell walls. The first experiments in wall coated-cell spectroscopy were done in the fifties. The early interest in this technique slowed rapidly down, mainly because of the technological difficulties connected with the melting temperature, the aging and the quality reproducibility of the coating. Recently the interest in wall-coated cells is growing again because coated cells represent a good candidate to realize mini-devices [2].

In this communication we present our preliminary results to develop a clock based on continuous lin||lin CPT-effect occurring in a paraffin wall-coated cell. Remark that the CPT-effect in wall-coated cells have not be studied much so far. Thus, even though the paraffin coating is not suitable for applications (mainly because of its low melting temperature), we are interested in understanding which kind of performances we can attain in a CPT-clock based on the use of wall-coated cells and if there is fundamental blocking point for this approach.

We monitor the light transmitted through the cell when the detuning between two resonant frequencies in the laser spectrum is spanned around the hyperfine splitting of the hyperfine ground states (ν_{HF}). We work with ^{87}Rb isotope contained in a cylindrical cell which has the external diameter and length both equal to 14 mm. To preserve the coating quality (i.e. anti-relaxation characteristics), it is necessary to keep the Rb metal in the cell stem and avoid the deposits in the cell walls. Thus, the temperature of the cell is controlled by two independently stabilized heaters. One heater sets the temperature of the cell stem (Ts), in which there is the alkali metal; the second heater sets the temperature of the volume (Tv) of the cell in which the light-atoms interaction occurs. The laser source used in the experiments, is a Distributed Feed-Back (DFB) diode laser emitting at 795 nm, e. g. resonant with the D1 line of ^{87}Rb (hyperfine separation ν_{HF}=6.8341 GHz). The DFB light is coupled into an optical fiber and it is modulated at about ν_{HF} through an Electro-Optical Modulator (EOM). The phase modulation index (M) is about 1.5 and it has been measured with a Fabry-Perot interferometer. For this value of M, the laser power is mainly distributed in the carrier and the first order sidebands, which have the same power. The laser is stabilized using a separate evacuated uncoated cell on the Doppler-free peak (transition $|F_g=2\rangle \rightarrow |F_e=1\rangle$). The cell is inside a μ-metal cylinder placed to shield the external magnetic field. Moreover, the residual field is compensated using three pairs of solenoid in configuration Helmholtz. The signal transmitted through the cell is collected on a photo-detector and monitored with a digital oscilloscope and a lock-in amplifier.

We studied the CPT–reference signal depending on the laser polarization with the objective of maximizing the contrast and minimizing the line-width of the resonance. The optimal conditions are reached when the laser is resonant to the group of transitions towards F_e = 1 and is linearly polarized (the so-called lin||lin CPT) [3].

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II. PRELIMINARLY EXPERIMENTAL RESULTS

A. Expected short-term stability

The short-term stability of an atomic clock can be predicted by the following formula [4]:

$$\sigma_y(\tau) = \frac{k}{Q \cdot S/N} \cdot \tau^{-1/2} \quad (1)$$

In Eq. (1), S is the reference signal amplitude; N is the detection noise expressed in terms of noise density; k is a constant that depends on the type of modulation used and is of the order of 0.2; and Q is the resonance quality factor.

A typical CPT-reference signal is shown in Fig. 1. In this case the temperatures of the cell Ts and Tv were 55 °C and 60 °C, respectively. The contrast of the signal, defined as the ratio between the variation of the transmitted light due to the CPT effect and the background level on the photo-detector, is about 2%. This value can be improved by increasing the diameter of the laser beam which is in this case about 10 times smaller than the cell diameter. The reference signal has a line-width of few hundreds Hertz (Q-factor ~ 10^7). In the optimal clock conditions, at present, the main contribution to the signal broadening is due to the optical power broadening.

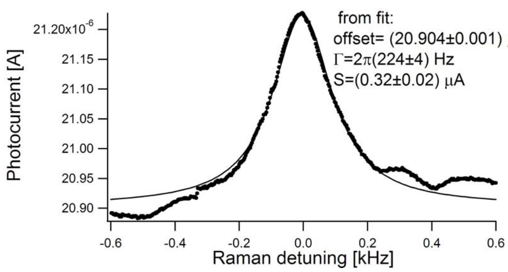

Figure 1. Example of reference signal. The Raman detuning is the difference between the frequency detuning of the two resonant frequencies in the light beam and the microwave hyperfine transition. The central frequency (0.0 kHz) correspond to ν_{HF}=6.83468239 GHz. The line-width and amplitude are approximately, $(\Gamma/2\pi)$=(224±4) Hz and S=(0.32±0.02) μA, respectively.

The shot-noise (N_s) corresponding to the experimental conditions of Fig. 1, is Ns= 0.3 pA·$Hz^{-1/2}$. We measured the detection noise for different Fourier frequencies and at different values of the one-photon laser detuning, either when the laser was modulated at ν_{HF} or not-modulated. From our noise-measurements we conclude that the most important contribution to the detection noise is due to the laser modulation at the microwave frequency. This contribution has two possible interpretations: (1) the noise of the micro-wave source which was not highly stabilized on an external reference; (2) the FM-to-AM conversion due to the off-resonance side-bands in the spectrum of the modulated laser. We are performing further measurements to clarify the origin of the detection noise.

In Table 1, the comparison of the estimate short-term stability for different noise conditions is shown. In particular we calculated $\sigma_y(\tau)$ taking into account the detection noise contributions for two Fourier frequency (ν_F=100 Hz and ν_F=16 kHz), corresponding to the typical detection frequency values when lock-in is used.

The estimated values for the short-term stability are comparable with the performance demonstrated in buffer gas cell for the pulsed CPT [5], the pulsed optical pumping [6] and continuous optical pumping [7]. Thus, the use of wall-coated cells seems very promising for achieving high performance secondary frequency standards suitable for laboratory use.

TABLE I. COMPARISON BETWEEN THE EXPECTED SHORT-TERM STABILITY

Noise (A $Hz^{-1/2}$)	Expected short-term stability, $\sigma_y(\tau)$
$N_s = 3\cdot 10^{-13}$	$4 \cdot 10^{-14}\,\tau^{-1/2}$
$N(\nu_F$ =100 Hz)= $2\cdot 10^{-10}$	$6\cdot 10^{-12}\,\tau^{-1/2}$
$N(\nu_F$ =16 kHz)= $2\cdot 10^{-11}$	$4 \cdot 10^{-13}\,\tau^{-1/2}$

B. Effects of the cell temperature

We present our preliminary study on the effects of the cell temperature on the clock reference signal which has not been studied in wall coated cells so far to the best of our knowledge.

To separate the effect of the cell temperature and of the resonance light, we study the behavior of the resonance parameters depending on the laser intensity for different temperatures (Ts, Tv). Ts and Tv are the temperature of the cell stem and volume and, in first approximation, they define the Rb density and the atomic velocity, respectively. (Ts, Tv) are in the range [25° C; 60°C]. The highest temperature limit is set by the coating properties (paraffin melting point is about 80°C); and the lowest temperature limit is set by the room temperature (about 22°C).

The dependence of the CPT-reference signal on the laser intensity can be roughly understood by means of a simple, three-level model [8]. The density matrix calculation for a symmetric three-level model isolated, predicts that the resonance will be Lorentzian with line-width (Γ) and amplitude (S):

$$\Gamma = 2\Gamma_{12} + \frac{\Omega^2}{\Gamma_{opt}} \quad (2)$$

$$S \propto \frac{(\Omega^4/\Gamma^3)}{2\Gamma_{12} + \Omega^2/\Gamma_{opt}} \quad (3)$$

In Eq. (2) and (3) Γ_{12} and Γ_{opt} are the relaxation rates of the ground- and excited-states coherence, respectively; Ω is the optical Rabi frequency such as $\Omega \propto kI_L$, where I_L is the resonant laser intensity

This simplified model is valid for a single atom at rest and in the case of resonant low-intensity light fields. Thus, this model cannot describe accurately the light-interaction scheme in a wall-coated cell, essentially because the atomic motion plays a not negligible role. However, it can be use to reproduce the trend of the resonance parameters depending on the laser intensity. We used eq. 2 and eq. 3 to fit the experimental data. The results are presented in Fig. 2 A and B, for three sets of temperature values (Ts, Tv).

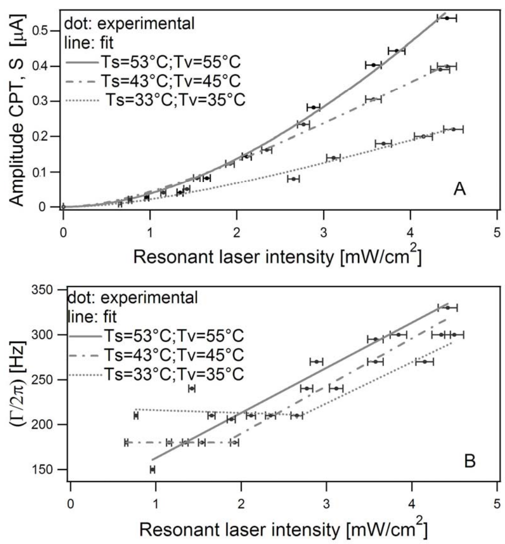

Figure 2. A. Amplitude and B. Linewidth of the CPT-reference signal depending on the laser resonant intensity for three sets of cell temperature .

The amplitude, S (Fig. 2 A) is proportional to the number of atoms in the dark state. S increases quadratically on laser intensity if $(\Omega^2/\Gamma_{opt}) \ll 2\Gamma_{12}$, then linearly. The amplitude of the CPT-reference signal increases when the temperature of the cell increases, as expected, essentially because of the enhancement of the Rb density. At low laser intensity this effect is not recorded because the diameter of the beam is noticeably smaller than the diameter of the cell. As a consequence the effect of the Rb density variation is averaged down by the atom motion.

The line-width of the CPT-reference signal (Fig. 2B), Γ, increases linearly with the laser intensity. In our experiments, at low resonant laser intensity ($I_L \rightarrow 0$ mW cm^{-2}), Γ can be limited by the spin-exchange relaxation rate, the atom-wall collision relaxation rate and time-of-flight relaxation rate. Remark that our experiments are performed with the same laser source, thus, the influence of the laser broadening in the resonance line-width cannot be evidenced. Decreasing the temperature (Ts, Tv), the experimental points of Fig. 2 B shows a saturation behavior at low laser intensity. We associate this saturation to the effect of atom-wall coating collision. The relaxation of the dark states due to the coating effect mainly occurs when the atoms is stuck in the coating material [9]. Qualitatively, we can imagine that when the cell temperature increases, the atomic velocity also increases and the sticking time decreases. As a consequence, at high temperature the influence of the coating should be less important than at low temperature, and, in fact, no saturation of the resonance linewidth is recorded.

III. CONCLUSION

We present our evaluation of lin||lin CPT-reference signal prepared in wall coated cell for clock applications. Based on our signal-to-noise measurements, we expect to reach a short-term stability < $10^{-12}\ \tau^{-1/2}$, while its intrinsic limit, i.e. the short-term stability shot noise limited is < $10^{-13}\ \tau^{-1/2}$. We also discuss our preliminary experiments to characterize the cell temperature effect. Next experiments will be devoted to the detailed characterization of the temperature influence on the resonance (including the shifts). In particular, we want to address the problem of the resonance dependence on the atomic motion which is negligible in buffer gas cell, and it is the new physical feature in the wall-coated cell.

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