Frequency Stability Measurement of a Raman-Ramsey Cs Clock

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Abstract— **CPT clocks are studied worldwide as miniature frequency standards for portable applications. To improve their frequency stability, we have investigated the optimum operating conditions (cell temperature, laser intensity, interrogation method) and measured the corresponding frequency shifts and stability. Compared to the continuous CPT interrogation, the pulsed interrogation reduces the light shift by a factor 300 and improves the frequency stability by a factor 10. The short term frequency stability is 9×10^{-13} at 1 s, limited to 2×10^{-13} after 300 s.**

I. Introduction

The coherent population trapping (CPT) phenomenon [1], [2] is a promising way in the realization of miniature atomic clocks or onboard compact clocks for navigation or telecommunication systems. CPT occurs when two coherent laser beams connect two ground states to a common excited state, forming the so-called Lambda scheme. On resonance, when the laser frequency difference is equal to the ground state hyperfine splitting, the atoms are trapped in a state superposition which does not absorb the light, called dark state. Unlike conventional microwave passive standards, the advantages of CPT are: no microwave cavity and no preparation of the atomic state before the microwave interrogation and atomic signal detection. The same laser interaction does all at the same time. The setup is simpler and the duration of an interrogation cycle can then be greatly reduced.

We have shown that high contrast and narrow linewidths, with relatively high laser intensities, were possible using crossed linear laser polarizations and the Ramsey interrogation method [3]. Using crossed linear laser polarizations allows to realize simultaneously two Λ schemes between the two clock levels ($m = 0$, m is the quantum Zeeman number) and the excited levels $m = \pm 1$. Double Λ schemes significantly increase the clock signal and its contrast. The observation of narrow linewidth in a vapour cell needs using buffer gas cells or wall coated cells, which shift the resonance frequency and can reduce the short or long term frequency stability of the standard.

In this paper we investigate some of the parameters affecting the stability of a buffer gas cell Cs standard. The signal can be increased by increasing the Cs density, which is easily realized by a temperature elevation. However collisions and absorption increase also reducing the signal. A study of the contrast as a function of the cell temperature is presented in section III, after the description of our experimental setup in section II. The contrast can be more than doubled at the optimum temperature. The temperature shift and the effect of the laser power are then reported. The light shift is measured in two cases: with a classical continuous interrogation of the microwave transition, and using a Ramsey interrogation. It is greatly reduced in this last case. This comparison is also made for the frequency stability in section IV. We report the results obtained with the same experimental conditions except the time sequence. The best stability is measured with a Ramsey sequence. Finally a measurement with a short term stability $\sigma_y = 9 \times 10^{-13} \tau^{-1/2}$ is shown, which is limited by our microwave chain noise and can still be improved.

II. Experimental setup

The experimental scheme is shown in Fig. 1. The two laser

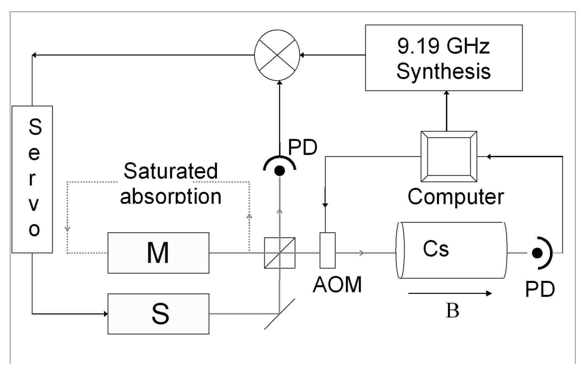

Fig. 1. Experimental setup. M and S are the master and slave diode lasers, AOM is the acousto-optic modulator, PD are photodiodes.

sources are laboratory made external-cavity diode lasers where the wavelength selection is assured by a narrow width and low loss interference filter instead of the usual diffraction grating [4]. The master laser is frequency locked to a hyperfine component of the Cs D1 line at 895 nm by saturated absorption in an auxiliary vapor cell. The slave laser is phase locked to the master with a tunable frequency difference around 9.2 GHz. Both beams are superposed on a polarizing cube and frequency shifted by an acousto-optic modulator for tuning on the Cs optical resonance in the cell, and simultaneously fast switching both laser beams intensity. The beams propagate through the cell along the axis of the applied static magnetic field B with linear orthogonal polarizations. The static magnetic field of about 10 μT is produced by a solenoid surrounded by two magnetic shields. The Cs cell, 50 mm long and 25 mm in diameter, holds in a temperature regulated enclosure. We have two cells, one filled with N_2 as buffer gas, and the other with a mixture of N_2 and Ar for temperature shift compensation.

The optical power transmitted through the gas cell is detected by a photodiode. The signal is then digitalized and processed by a computer which drives also the microwave synthesizer generating the frequency difference between the two lasers. The computer also drives the acousto-optic modulator switch.

III. Experimental results

We have studied the behavior of the CPT signal as a function of the cell temperature and the resonance frequency shift due to the laser power and collision rate. The figure 2 shows the effect of the cell temperature on the contrast of the $0-0$ resonance in the case of a continuous (CW) interrogation. The

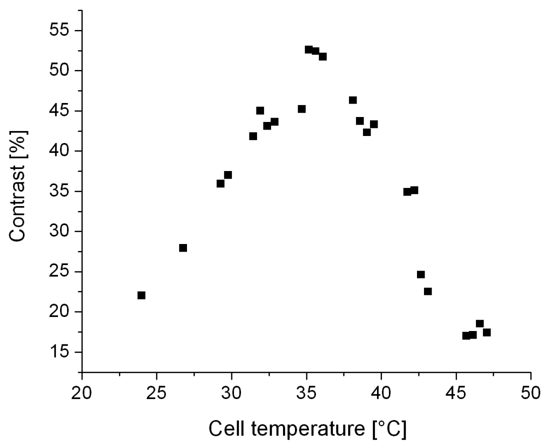

Fig. 2. Contrast of the clock signal versus the temperature of a N_2 Ar buffer gas cell. The laser power is 1.20 mW/beam with a beam diameter 13 mm.

contrast is defined as the ratio of the signal at resonance minus the signal off resonance to the signal at resonance. The cell used is the two buffer gas cell. The optimal value is a compromise between a high atomic density, a low collision rate, and the optical thickness. At room temperature, the contrast is 20%, it is already a high value for a gas cell standard due to our double Lambda scheme with linear orthogonal laser polarizations [3]. With the usual circular polarization the atoms are trapped in the extreme Zeemann sublevels by optical pumping effect, limiting the contrast to a few percent. The experimental maximum value 52% at 35°C is among the best contrasts obtained on a gas cell standard. The same optimum with temperature is found with a Ramsey interrogation.

Collisions with buffer gas shift the atomic frequencies. The frequency shift value depends of the nature of the gas, of the pressure and of the temperature. This affects the accuracy of the standard and also its stability because the cell temperature fluctuations or drifts. With the usual notations the frequency shift is written as [5]:

$$S = P(\beta + \delta t + \gamma t^2) \tag{1}$$

where S is in Hz, P is the buffer gas pressure (Torr) at 0°C, and t is the cell temperature (°C). According to Strumia et al. [6] $\beta = 924.7$ Hz Torr^{-1}, $\delta = 0.62$ Hz Torr^{-1} C^{-1}. To our knowledge γ was unknown until now. The frequency shift of the clock resonance with the temperature is shown on Fig. 3 for a commercial cell filled at room temperature with 23 Torr of nitrogen. A fit of the experimental points with P and γ

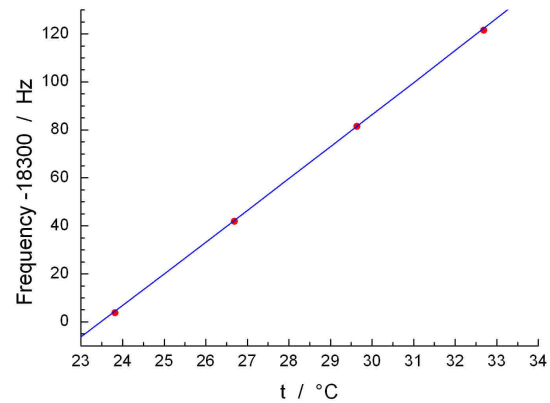

Fig. 3. Frequency shift of the resonance with the cell temperature. The buffer gas is N_2. Dots: experimental points, line:quadratic fit.

as fitting parameters gives $P = 21$ Torr at room temperature and $\gamma = (1.06 \pm 0.3) \times 10^{-3}$ Hz Torr^{-1} C^{-2}. This value should be considered as an order of magnitude as we don't know the real pressure in the cell and its uncertainty, neither the sealing temperature. The linear shift measured on the N_2-Ar cell is -2.3 Hz C^{-1}, i.e. six times less than for N_2 cell. Ar is employed because it has a linear temperature coefficient with the opposite sign of N_2. Its quadratic coefficient is also unknown and has to be measured in order to be able to choose the good mixture composition which will minimize the temperature dependence.

The figure 4 shows the light shifts measured in two cases: with a continuous interrogation and a Ramsey interrogation. The measurements are performed with lasers of equal intensities; the microwave frequency is locked on the resonance using a square wave frequency modulation and the averaged frequency is recorded. The shifts are quite linear with the laser intensities. We measure a slope of -10.84 Hz mW^{-1} cm^2 (-1.2×10^{-9}mW^{-1} cm^2 in relative value) with the continuous interrogation and -0.035mW^{-1} cm^2 (-3.8×10^{-12} mW^{-1} cm^2) with the Ramsey interrogation, i.e. 300 times less. In the continuous case the duration of a half cycle is 6.5 ms. The parameters of Ramsey sequence are 2 ms pumping time and 4.5 ms free evolution time. By using longer pumping time the light shift increases proportionally and becomes comparable to the one measured in the CW regime. We would point out

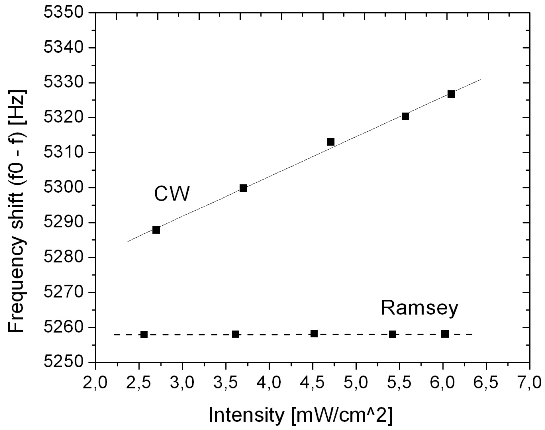

Fig. 4. Resonance frequency shift versus the laser intensities. Solid line: CW interrogation, dashed line: Ramsey interrogation. The intensity reported on the horizontal axis is the sum of the two equal laser intensities; $(f_0 - f)$ is reported on the y axis with f_0 the frequency of the second definition and f the resonance frequency corrected for the quadratic Zeeman effect.

here the light shift reduction by the Ramsey technique, not the numerical values of the shifts which depend on the buffer gas [7].

IV. Frequency stability

We have measured the short term frequency stability obtained in two cases: CW interrogation and Ramsey interrogation. The stabilities are measured against a hydrogen maser of the laboratory. The time sequence parameters are the same as above. The used cell is also the two gas cell. The resonance linewidth is 1 kHz in the CW case and 100 Hz with the Ramsey technique. The Allan standard deviations $\sigma_y(\tau)$ are shown in Fig. 5. For averaging times τ between 1 s and

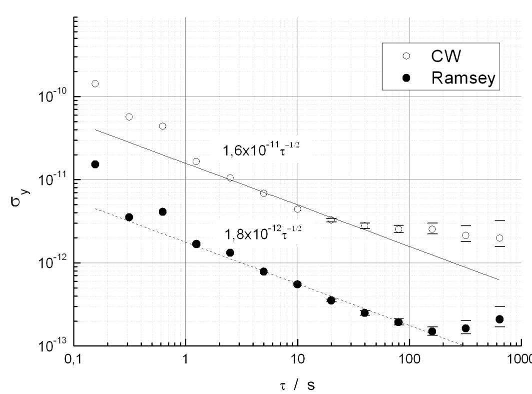

Fig. 5. Allan standard deviations $\sigma_y(\tau)$. Open circles: CW interrogation, full circles: Ramsey interrogation. Both curves are obtained in the same conditions, cell temperature 27°C, laser power 1.2 mW each beam, beam diameter 13 mm.

about 100 s the slopes are respectively $1.6 \times 10^{-11}\tau^{-1/2}$ and $1.8 \times 10^{-12}\tau^{-1/2}$ for the CW and Ramsey interrogations. The difference is due mainly to the narrower linewidth of the Ramsey interrogation. This result clearly shows the advantage of the Ramsey method. In this case indeed the short term stability is limited by the phase noise of our microwave chain and should be still improved. The main noise contributions to the Allan deviation calculated at 1 s are reported in Table I. The contribution of the shot noise is less than 10^{-14}. In

Noise Source	σ(1 s)
Microwave chain phase noise	1.4×10^{-12}
Maser phase noise	4×10^{-13}
Photodetector noise	3.2×10^{-13}
Amplitude noise induced by laser intensity noise	Not evaluated
Light shift induced by laser intensity noise	10^{-14}

TABLE I

Main contributions to the short term stability

order to evaluate the effect of the laser intensity noise on the the frequency stability via the light shift we have measured the relative Allan standard deviation of the laser powers, see Fig. 6. The measurement is performed in the same conditions

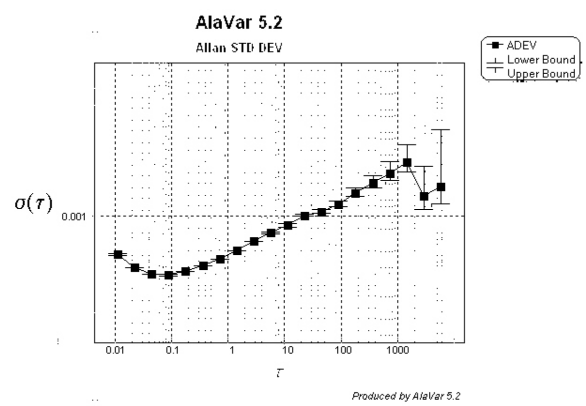

Fig. 6. Relative Allan standard deviation of the sum of the laser powers. Laser power 1 mW, beam diameter 13 mm.

as the frequency measurements but with the Cs cell removed. The signal is the sum of the two laser powers.

The frequency stability has been measured for longer time, see Fig. 7. The short term stability is $9 \times 10^{-13}\tau^{-1/2}$ for averaging time between 0.5 and 30 s, which is one of the better value reported for a cell frequency standard [8], [9], [10], [11], [12]. This better stability is due to a reduction of the phase noise of our microwave chain which still limits the short term stability. For longer averaging time the stability rises as $\tau^{1/2}$, corresponding to a random walk of frequency noise. It can be explained by thermal effects. In this measurement the N_2 cell at 30°C was used which has a larger thermal coefficient. This also explains why the stability rises for times shorter than in Fig. 5 where the two buffer gas cell was used. The main limitations to the mid term stability are the temperature shift and the effect of the magnetic field estimated at a few 10^{-13} for each one. The effect of light shift computed from previous

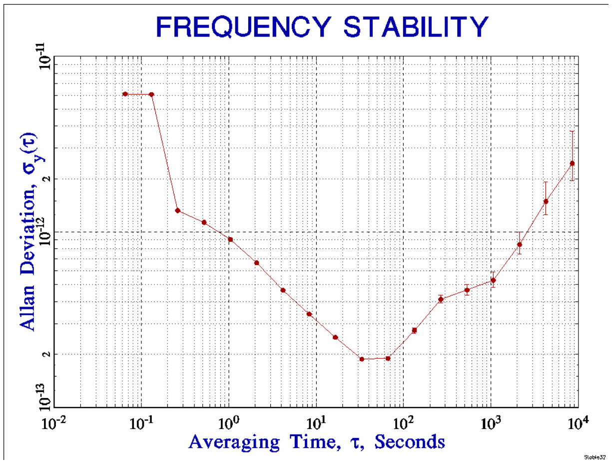

Fig. 7. Allan standard deviation y(t). Experimental conditions: Ramsey interrogation, N_2 cell at 30°C, laser power 0.75 mW.

measurements would give a stability of 3×10^{-14} at 1000 s and is not yet a limitation.

V. Summary and perspectives

We have investigated some of the parameters affecting the stability of a Cs cell CPT frequency standard. The contrast can be raised from 20% to more than 50% by heating the cell. This high value is only possible because we use a double Lamda configuration. Two frequency shifts are investigated: the cell temperature effect and the laser intensity effect. The temperature shift has been measured for a N_2 cell and a first measurement of the quadratic coefficient is reported. The light shift is reported for two cases: a continuous interrogation and a Ramsey interrogation. Its value is reduced by a factor 300 with the Ramsey technique to 35 mHz mW^{-1} cm^2. The short term frequency stability is divided by 10 using the Ramsey technique compared to a CW interrogation. The stability is limited by the phase noise of our frequency chain and not by the light shift. The best stability reported is $\sigma_y(\tau) = 9 \times 10^{-13}\tau^{-1/2}$ for 0.5 s $< \tau <$ 30 s and can still be improved using a lower phase noise microwave synthesis. To our knowledge this stability is the best reported for a CPT standard. For longer averaging time the stability raising is explained by thermal effects which can be reduced by using a correct mixture of buffer gases. An alternative to the buffer gas is the use of a wall coated cell. We have measured the relaxation time T_1 in a paraffin coated cell (diameter 20 mm) kindly furnished by the University of Fribourg. The measurement is performed by recording the Ramsey signal as a function of the free evolution time. We have obtained $T_1 = 37$ ms, which is about 4 times longer than in our buffer gas cells.

These results show the possibility of a gas cell CPT standard with a short term frequency stability of a few 10^{-13} at 1 s.

VI. Acknowledgment

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