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RECENT RESULTS OF THE PULSED OPTICALLY PUMPED RUBIDIUM CLOCK

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ABSTRACT

A laboratory prototype of a pulsed optically pumped (POP) clock based on a rubidium cell with buffer gas is described. This clock has shown very interesting physical and metrological features, such as negligible light-shift, strongly reduced cavity-pulling and very good frequency stability. In this regard, an Allan deviation of $\sigma_y(\tau) = 1.2 \tau^{-1/2}$ for measurement times up to $\tau = 10^5$ s has been measured. These results confirm the interesting perspectives of such a frequency standard and make it very attractive for several technological applications, such as radionavigation.

1. INTRODUCTION

Light shift is recognized as one of the main physical effects limiting the medium term frequency stability of optically pumped vapor-cell clocks. Also in the most recent clocks where the optical pumping is done with a narrow-band laser source, light shift could be even worse. This is basically due to the higher level of atomic optical coherences excited by the laser, resulting then in a relevant noise conversion from the laser itself to the clock signal.

A partial reduction of these problems can be achieved with the lambda configuration where the atoms are excited in a more symmetrical excitation scheme, but, in this way, the physical effects which impair the frequency stability may be compensated or reduced but not fully eliminated.

One of the more effective technique to reduce light shift is the pulsed scheme where the optical pumping phase is separate in time from the microwave excitation, in such a way that the clock transition is observed in a nearly pure two level system. The coupling between optical and microwave coherences is avoided and a strong reduction of the light shift is achieved.

This idea was first considered by Alley [1] and applied to the field of frequency standards by Arditi and Carver [2]. We recently revisited this idea taking into account the technologies nowadays available, laser diodes and fast pulsed electronics, and taking also into account a deeper knowledge of the physics involved in this frequency standards [3]. In particular, we refer to a

POP frequency standard based on a diode laser for the optical pumping, on a Ramsey pattern for the microwave interrogation and on the observation of the atomic free-induction decay signal to detect the clock transition [4]. The detection of the coherence signal, after the double pulse Ramsey interaction, allows some advantages with respect to the more usual optical detection. First of all, the linewidth is reduced by a factor of $(\Delta\nu=1/4T)$, being T the Ramsey time). Other benefits of this technique come from the absence of any background signal and a significant reduction of the cavity pulling effect adjusting properly the power of the interrogating microwave, as demonstrated in [3]. In this paper we resume the interesting results obtained with a laboratory prototype of POP frequency standard.

2. THE EXPERIMENTAL PROTOTYPE

The experimental prototype we are going to describe in this section mainly implements the theoretical model reported in [3]. The atomic levels involved in the experiment are shown in Fig. 1. They refer to a sample of Rb atoms diluted in a buffer gas. Γ^* is the decay rate of the optical state $|m\rangle$, γ_1 and γ_2 are the relaxation rates of the population difference and of the coherence of the ground state hyperfine levels and ω_L and ω_0 are the laser and the microwave angular frequencies respectively.

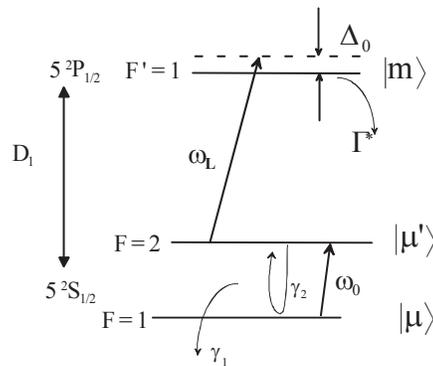


Fig. 1. ⁸⁷Rb three level system.

The experimental set-up is schematically reported in Fig. 2; it has three main sections: optics, physics package and electronics.

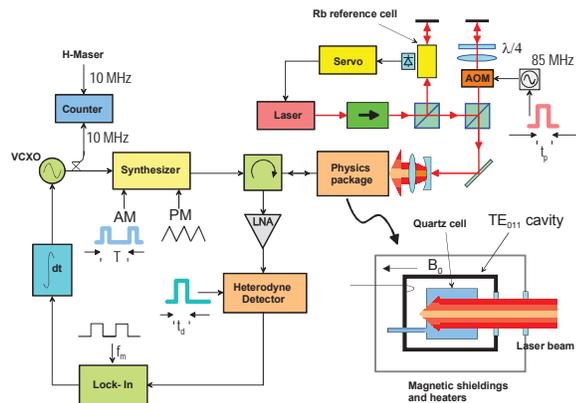


Fig. 2. Experimental set-up of the POP frequency standard.

Optics. A semiconductor diode laser provides a tunable radiation at 795 nm (^{87}Rb D₁ transition) and a power up to 4 mW. The laser frequency is locked to the optical transition via the Lamb-dip observed in a reference cell containing pure ^{87}Rb .

The main part of the laser beam is sent to the physics package through an acousto-optic modulator (AOM) operating in the double-pass configuration. The AOM acts as an optical switch required to perform the pulsed pumping of the atomic ensemble and shifts the laser frequency towards the red to match the absorption frequency of the atoms in the cell shifted by the buffer gas pressure (-6.8 MHz/Torr). The laser beam is expanded to a diameter of 2 cm and its power density is $I_L \approx 0.3 \text{ mW/cm}^2$ at the cell entrance.

Physics package. The core of the physics package is the quartz cell has an internal length of $L = 18 \text{ mm}$ and contains ^{87}Rb (98 %) and a thermally compensated buffer gas mixture of Ar and N_2 . The operating temperature of the cell is about $60 \text{ }^\circ\text{C}$, corresponding to an atomic density of $n = 3 \times 10^{11} / \text{cm}^3$. For this cell we have $\Gamma^* \approx 3 \times 10^9 \text{ s}^{-1}$, $\gamma_1 \approx \gamma_2 \approx 290 \text{ s}^{-1}$ and an optical length of $\zeta \approx 3.5$.

The microwave cavity is made of Al and is tuned to the hyperfine frequency of the ground state. It resonates on the TE₀₁₁ mode. When the quartz cell is inserted and the coupling is critical, the loaded quality factor is measured to be $Q_L \approx 10000$, while the filling factor is $\eta \approx 0.4$ [4]. The cavity is temperature stabilized at the level of 5 mK and placed inside a double magnetic shield; a longitudinal static magnetic field $B_0 \approx 10^{-5} \text{ T}$ defines the quantization axis.

Electronics. The microwave signal emitted by atoms can be detected with a heterodyne detector, while a lock in

amplifier and an integrator provide the control signal to a 10 MHz quartz. A synthesizer is amplitude modulated to provide the Ramsey pulses. The interrogation signal is frequency modulated with a square wave signal whose frequency is of course one half the cycle frequency. The clock operation is similar to that of an atomic fountain but in the POP the cycle is faster, being of the order of 10 ms.

More details on the experimental set-up are reported in [5].

The experimental set-up just described realizes the timing sequence of Fig. 3.

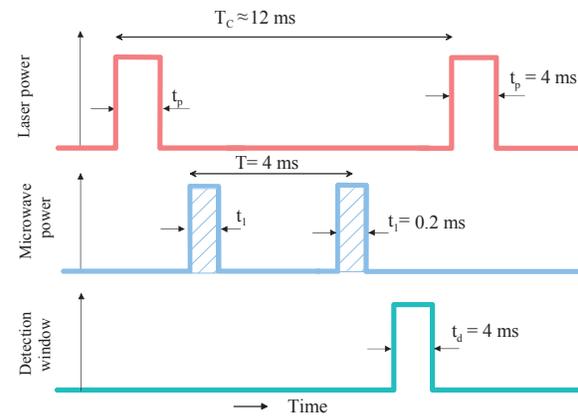


Fig. 3. Timing pattern of the pulsed scheme with typical values of the times involved in the clock operation; t_p optical pumping time, t_1 duration of the microwave pulse (Rabi time), T Ramsey time, t_d detection time, $T_C = t_p + 2t_1 + T + t_d$ cycle time.

3. RESULTS

Figure 4 shows a typical cavity output signal as detected by the spectrum analyzer.

To clarify the mechanism of the coherence destruction we used two lasers: a commercial diode laser with a power of about 1 mW at the entrance of the cell and a Ti: Sa laser with a power of 20 mW.

The free-induction decay signal between the two Ramsey pulses and after the second Ramsey pulse is clearly observed. This signal is proportional to the modulus squared of the coherence excited between the two ground state levels. The role of the laser pulse during the pumping phase is evident. The microwave coherence is strongly reduced so that at the beginning of the new cycle the atoms do not have memory of the previous one. Changing to a more powerful laser, the atoms generate a higher output signal, since a larger population inversion has been produced in the ground state and so more atoms participate to the Ramsey interaction. Moreover, the coherence destruction process is more efficient.

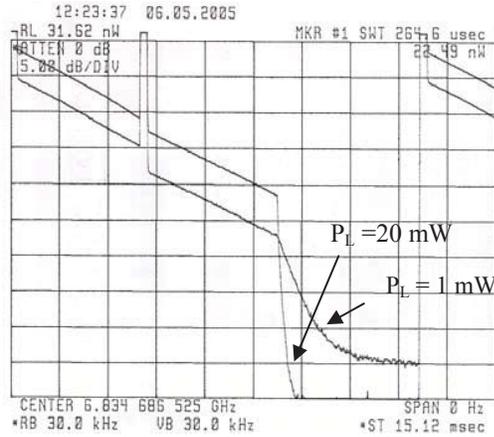


Fig. 4. Cavity output signal observed for two lasers. $P_L = 1$ mW: diode laser; $P_L = 20$ mW: Ti: Sa laser. Timing sequence: $t_1 = 220$ ms; $T = 4$ ms; $t_p = 4$ ms; $t_d = 3.8$ ms; $\theta = \pi/2$.

Ramsey fringes can be observed in the free induction decay signal by measuring the output power at the end of the second Ramsey pulse and then changing the microwave detuning, as observed in Fig. 5.

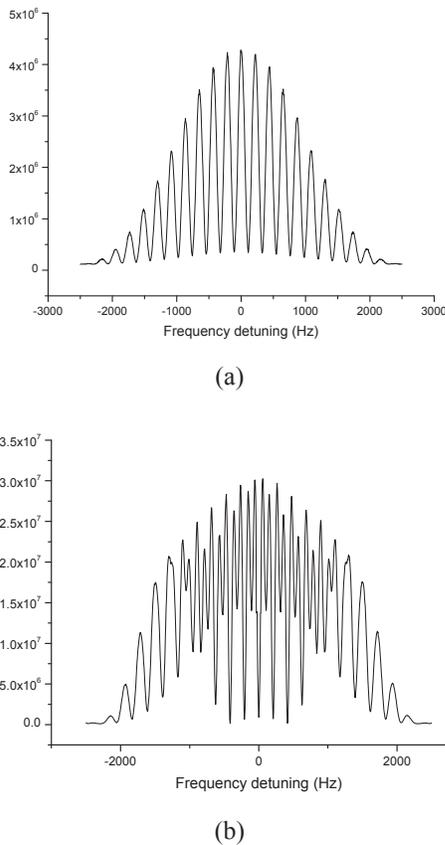


Fig. 5. Ramsey fringes detected in the microwave domain (free-induction decay signal); (a) $\theta = \pi/4$, (b) $\theta = \pi/2$.

The theoretical results mentioned before are clearly confirmed. The Ramsey fringe for $\theta = \pi/2$ (being θ the microwave pulse area, proportional to the amplitude) shows an atomic quality factor that is twice that of the fringe observed for a lower value of θ .

We measured the POP clock frequency versus the microwave pulse area q for three different values of the cavity detuning. According to the theory, there is a suitable value of q so that the clock frequency does not depend on the cavity detuning and then there is an operation point where the cavity pulling effect is minimized.

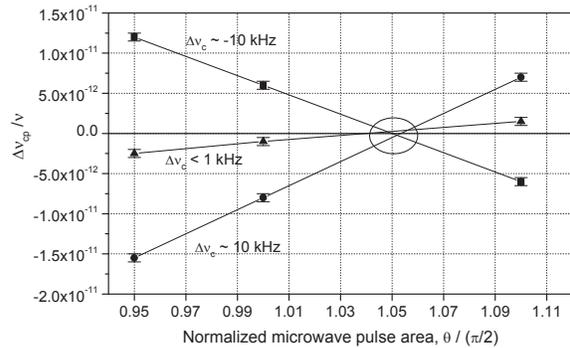


Fig. 6. Clock frequency versus θ for different values of the cavity detuning $\Delta\nu_C$.

In Fig. 7 we report the measured frequency stability of the POP frequency standard; the figure shows the overlapping Allan deviation and the Theo deviation.

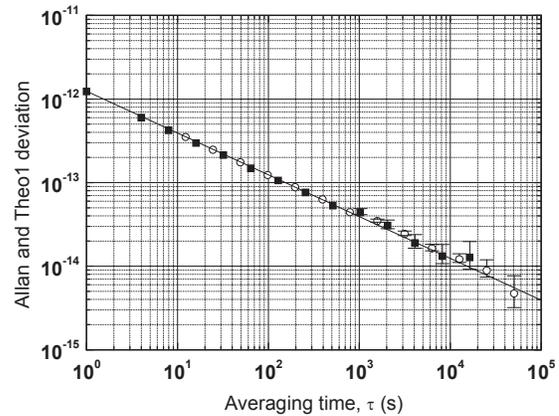


Fig. 7. Frequency stability; overlapping Allan deviation (black square), Theo deviation (open circle).

This result has been obtained with the following timing sequence: $t_1 = 400$ ms; $T = 4.6$ ms; $t_p = 1$ ms; $t_d = 2$ ms, and with a laser power of $I_L = 10$ mW/cm². A frequency drift of 6×10^{-14} per day has been removed to the raw data. In particular, the long term frequency behavior is

dominated by the buffer gas temperature coefficient, spin exchange shift and cavity pulling, under the hypothesis that the laser AM and FM noise fluctuations are not transferred to the observed microwave transition.

The last hypothesis is true if the following condition is satisfied [3]:

$$\Gamma_p \gg \zeta\gamma_1 + 1/t_p \quad (1)$$

being Γ_p the laser pumping rate.

In our experimental conditions we have $\Gamma_p \approx 10^5 \text{ s}^{-1}$ and $\zeta\gamma_1 + 1/t_p \approx 1300 \text{ s}^{-1}$ so that we can assume that the laser noise is rejected by the pulsed operation.

In Table I we estimate the relative frequency fluctuations of the POP clock due to the noise conversion from the laser to the microwave signal and due to the thermal instabilities through spin exchange, buffer gas and cavity pulling.

Noise /Drift Source	Transfer function
Laser PM-microwave PM	$1 \times 10^{-13} / \text{MHz}$
Laser AM-microwave PM	$5 \times 10^{-14} @ 1\%$ fluctuation
Spin exchange	$1 \times 10^{-11} / \text{K}$
Buffer Gas	$1 \times 10^{-11} / \text{K}$
Cavity Pulling	tunable to $< 1 \times 10^{-11} / \text{K}$

Table I. Main laser noise conversion factors and thermal sensitivity in the POP frequency standard.

We point out that, since spin exchange, buffer gas and cavity pulling are of the same order of magnitude (in absolute value), a proper choice of the Rabi pulse area allows a partial compensation of these effects, so that the overall temperature sensitivity of the clock frequency can be reduced to about $5 \times 10^{-12} / \text{K}$.

This means that the temperature of the cell should be controlled at the mK level in order to achieve a frequency stability in the 10^{-15} range.

The cavity containing the cell is the placed inside a double thermal shield whose temperature is actively controlled. Fig. 8 shows the temperature stability of the two shields and of the laboratory air. The temperature fluctuation of the innermost shield is $10 \mu\text{K}$, much better of the required value. The temperature of the internal loop shows a deterministic drift of about $50 \mu\text{K}$ a day.

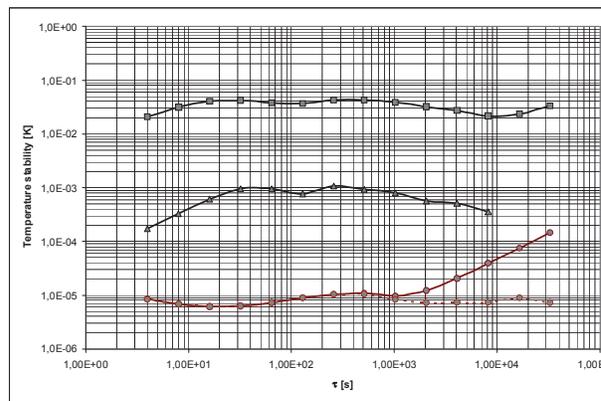


Fig. 8. Temperature stability; square: temperature stability of the laboratory air; triangle: temperature stability of the external thermal shield; circle: temperature stability of the cavity. Dot Line: drift removed data; continuous line: raw data.

4. CONCLUSIONS

In this paper we reported the physical and metrological properties of a laboratory prototype of POP frequency standard. The experimental results are in good agreement with the theoretical prediction reported in [3]. In particular, the observation of the microwave emission allows to double the quality factor of the atomic transition with respect to the optical detection, and furthermore reduces the impact of the laser noise. In suitable operating conditions, light shift and cavity pulling can be strongly reduced. The short-medium term frequency stability has been measured and the result is among the best obtained in optically pumped vapor cell devices. An optimization of the system can allow to reach a stability of $\sigma_y(\tau) = 7 \cdot 10^{-13} \tau^{-1/2}$; the possible improvements include a less noisy synthesis chain and an auto-tuned cavity to reduce the frequency drift.

Definitely, the results here reported show that a proper implementation of the POP clock is very attractive for several application where a simple and reliable device is required, such as the space applications.

5. REFERENCES

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