Improving short and long term stability of pulsed optically pumped vapor cell frequency standards

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***Abstract*—In this paper we discuss how to improve both short and medium–long term frequency stability of a vapor cell frequency standard working in pulsed regime. We propose in particular a multi-step pumping technique that is able to put almost all the atoms in one of the two clock levels, increasing in this way the signal-to-noise ratio with respect to the usual optical pumping made with a single laser pulse. Moreover, we discuss the phenomena affecting the medium-long term frequency stability and how it is possible to control them, making the overall clock stability compatible with $\sigma_y(\tau) = 3x10^{-13}\ \tau^{-1/2}$ for integration times up to $\tau = 10^5$ s.**

I. INTRODUCTION

Recently several schemes have been proposed to reduce light shift in a laser pumped vapor cell frequency standard, improving at the same time the stability perspectives of these clocks [1, 2, 3]. Pulsing the different operation phases of a vapor cell clock has been recently recognized as one of the most effective technique in this regard.

In particular, the Pulsed Optically Pumped (POP) rubidium maser prototype we implemented at INRIM has achieved very interesting results: a frequency stability (Allan deviation) of $\sigma_y(\tau) = 1.2x\ 10^{-12}\ \tau^{-1/2}$ for integration times up to $\tau = 10^5$ s has been measured and the 10^{-15} region, after drift removal, has been reached . With the goal of improving these results, we discuss in this work two main aspects. The first one concerns the possibility to improve the short term stability of the clock. This can be done with a new pumping technique (applicable to both microwave and optical detection) consisting of a suitable sequence of laser and microwave pulses that put most of the ground state atoms in one of the clock levels. The possibility of increasing in this way the clock signal even of a factor of three has been demonstrated.

The second topic concerns the physical phenomena that may affect the medium-long term frequency stability of pulsed optically pumped vapor cell frequency standards and how it is possible to reduce them. As well known, the fluctuations of the following physical quantities have been recognized as sources of frequency instability in the medium long term: environmental quantities (temperature, atmospheric pressure, relative humidity), quantization magnetic field, power of the interrogating microwave (if present), intensity and frequency of the laser used for optical pumping. We will show that the possibility of pulsing the different phases of operation of a vapor cell clock (POP technique but in principle also pulsed EIT) allows to control the medium-long term effects in such a way to make them compatible with a flicker floor well below 10^{-14} for extended measurement times.

II. IMPROVING THE SHORT TERM STABILITY: THE TOTAL PUMPING TECHNIQUE

It is well known that the short term frequency stability achievable by an atomic clock depends on the number of atoms making the clock transition. In a vapor cell clock working in pulsed regime it is possible to concentrate almost all the atoms in one of the two clock levels with the total pumping technique described later.

In the following we refer to the apparatus shown in Fig. 1 and described in detail in [1].

A quartz cell containing a ^{87}Rb vapor and a mixture of buffer gas is placed in a microwave cavity resonant to the hyperfine ground state transition frequency (6.834 GHz).

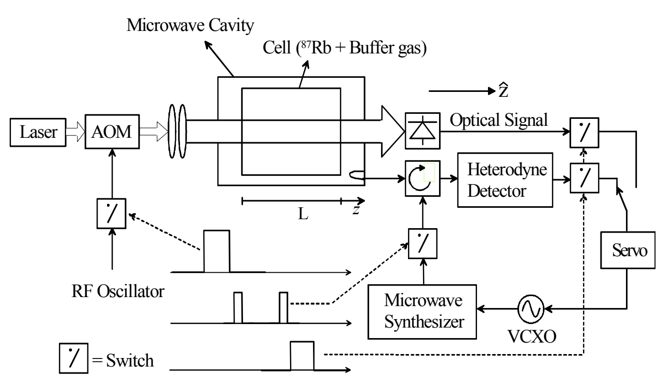

Figure 1. Experimental apparatus used to demonstrate the total pumping technique.

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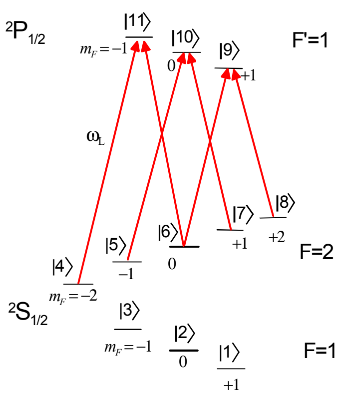
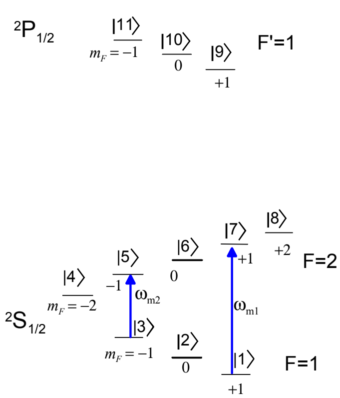
The common optical pumping technique used to invert the population between the clock levels is substituted by a suitable sequence of laser and microwave pulses after which up to 95% of the atoms can be prepared in one of the two clock levels with m_F=0.

With reference to Fig. 2, in (a) a laser pulse is applied to the atomic sample at the end of which the atoms are equally distributed among the F=1 sublevels; after the laser pulse, the atoms are submitted to π microwave pulses that completely invert the atomic populations between the connected levels, as shown in (b). The atoms experience several of these alternating laser pumping-microwave pulses cycles up to most of the atoms are transferred to the clock level $|F = 1, m_F = 0\rangle$.

As consequence of this multiple laser-microwave pumping the population of the clock level increases step by step.



(a)



(b)

Figure 2. Multiple pumping sequence; (a) laser pulse at the end of which the atoms are equally distributed among the F=1 sublevels; (b) π microwave pulses to invert completely the atomic populations between the connected levels.

Fig. 3 shows the computed values of the relative population of level |2>, in terms of the density matrix element ρ_{22}. The figure refers to a temperature of 36 °C (low atomic density), and two values of the laser pumping rate (Γ_p), proportional to the laser intensity, are considered.

In our experimental set-up, the laser intensity at the entrance of the cell is about 2 mW/cm^2, corresponding to $\Gamma_p \approx$ 25000 s^{-1}. Therefore, we are able to put up to the 80 % of the total atomic population in the interested level. With a more powerful laser the population in level |2> can reach 95%.

When the apparatus works as a clock, it is important to not increase the pumping time in order to not increase the total cycle time. Moreover, in our case the clock transition is observed in the form of a maser emission due to the coherence generated in the atomic ensemble, the so called POP maser.

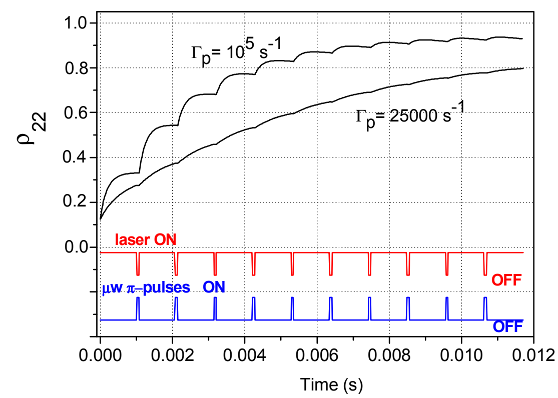


Figure 3. Calculated relative population of level |2>.

We measured the maser output power versus the number of laser pulses keeping the total optical pumping time equal t_p = 4 ms. As shown in Fig. 4, the total pumping scheme allows to obtain a signal up to three times larger than that achievable by a traditional optical pumping realized with a single laser pulse. Theoretical analysis based on a multilevel approach [4] and experiment are in very good agreement.

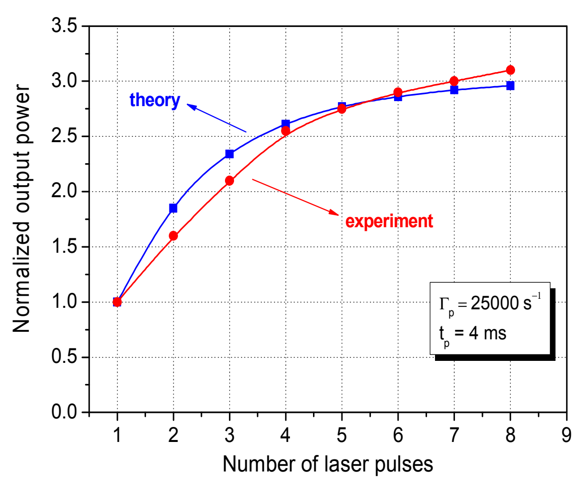


Figure 4. Circles: measured output power versus the number of laser pulses for a total optical pumping of t_p= 4 ms, Γ_p = 25000 s^{-1}; squares: corresponding theoretical curve.

To show further the effectiveness of this technique we measured the clock frequency stability of the POP maser clock frequency stability in two cases; the upper curve refers to a conventional optical pumping made with a single laser pulse of 4 ms, while the lower curve refers to a multi-step optical-microwave pumping made with nine laser pulse of length 444 µs each. An improvement of the order of a factor of two is achieved.

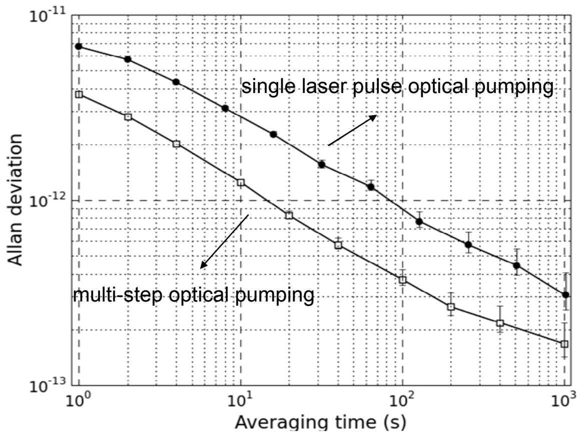


Figure 5. POP maser frequency stability in the case of traditional optical pumping (upper curve) or multistep optical pumping (lower curve).

We point out that this scheme can be used to put atoms in level |1> or |3> if desired, or can be extended as well also to Cs, provided a proper number of microwave π pulses is applied to the Cs atoms.

III. Improving the Medium-Long Term Stability

Improving the medium-long term frequency stability of an atomic clock means to know the physical quantities whose fluctuations are directly transferred to the clock frequency through one or more physical effects. We recognize: 1) the environmental parameters, such as the temperature T_0, the atmospheric pressure P and the relative humidity $u\%$; 2) the quantization magnetic field, B_0 3) the power of the interrogating microwave signal, P_{mw}; 4) the power P_L and the frequency ν_L of the laser used for optical pumping.

Figure 6 summarizes these effects.

Table I summarizes the conversion factors of the several effects and their respective contributions to the Allan deviation of the clock as measured or evaluated for our laboratory prototype of Rb POP maser. From the values reported in the table it turns out that the cavity should be placed in a vacuum chamber to eliminate the transfer of the barometric pressure to the clock resonance (Clausius-Mossotti equation). In this case, the overall contribution to the Allan deviation is of the order of 5×10^{-15}.

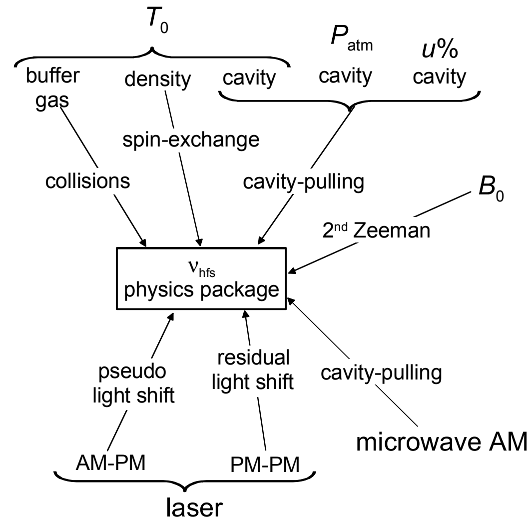


Figure 6. Physical quantities whose fluctuations are transferred to the clock transition through the respective physical effects.

TABLE I

Effect	Conversion factor	Physical quantity	$\sigma_y(\tau)$ τ up to 10^5 s
Zeeman 2nd order	3.4×10^{-9}/G	B_0	3×10^{-16}
Buffer gas	6×10^{-12}/°C	T_0	2×10^{-16}
Spin-exchange	5×10^{-14}/°C		6×10^{-17}
Cavity-pulling	2×10^{-11}/°C		6×10^{-16}
	1×10^{-15}/Pa	P_{atm}	4×10^{-13}
	4×10^{-14}/%	$u\%$	4×10^{-16}
	2×10^{-13}/%	P_{mw}	3×10^{-15}
	1×10^{-14}/%	P_L	3×10^{-15}
Light-shift	2×10^{-15}/%		6×10^{-16}
	2×10^{-14}/MHz	ν_L	1×10^{-16}
total = $\left(\sum_i \sigma_{y_i}^2\right)^{1/2}$			5×10^{-15}

Also in this way, however, the main contributions to the frequency instability come from cavity pulling, that is in fact related to the feedback of the cavity on the atoms; in pulsed operation with Ramsey scheme, the effect of the feedback is important during the Ramsey time T.

It is then possible to implement a cavity Q-switching technique during the Ramsey time using a Schottky diode coupled to the cavity through the TE_{011} electromagnetic mode.

The cavity pulling effect is in this way reduced by a factor t_1/T, being t_1 the Rabi time.

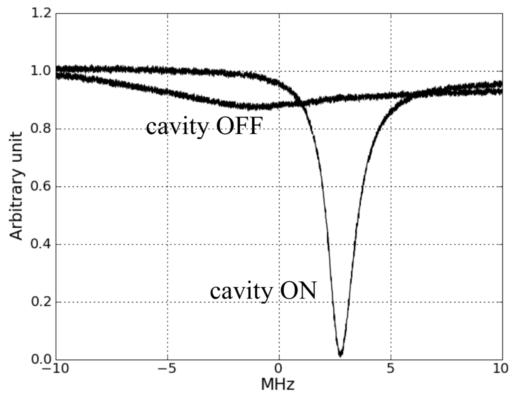


Figure 7. Power reflected out of a microwave cavity coupled to a Schottky diode. When the diode is forward biased the cavity Q is destroyed, while in the reverse bias condition the diode can be used to tune the cavity.

Another important point concerns the spatial distribution of the electromagnetic mode inside the cavity: the spatial region where the atomic sample is placed should be as uniform as possible; an optimization of the relative sizes cell/cavity is then required [4].

The variation of the physical quantities responsible of the previous effects can be transferred to the clock resonance also in the form of frequency drift. The previous technical improvements allow to reach a limiting floor of 1×10^{-15} for $\tau \leq 10^5$ s and to limit the overall drift to 4×10^{-15}/day [5].

IV. CONCLUSION

In conclusion, in this work we have shown that it is possible to improve both the short term and the medium-long term of a vapor cell clock working in pulsed regime. In particular, a new pumping technique has been proposed to increase the number of atoms making the clock transition and increasing consequently the signal-to-noise ratio.

The data here reported obtained with a lab prototype of POP Rb maser are in good agreement with the theory developed in [4]. Moreover, it is possible to control the medium-long term effects so that to make them compatible with $\sigma_y(\tau) = 3\times 10^{-13}\ \tau^{-1/2}$ for integration times up to $\tau = 10^5$ s

ACKNOWLEDGMENT

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