Recent results on a pulsed CPT clock

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***Abstract*— CPT clocks are very attractive for their miniaturization potentiality. Nevertheless, two main effects limit today their performance : the optical pumping associated with circularly polarized lasers and the line broadening due to saturation effects. We propose to overcome these limitations by the use of orthogonal linear laser polarizations and a pulsed interrogation sequence. The optimization of the time sequence leading to the best characteristics (contrast, linewidth) of the dark resonance is discussed. Very preliminary measurements of the frequency stability demonstrate an interesting performance of $3.5\ 10^{-12}\tau^{-1/2}$**

I. INTRODUCTION

Coherent Population Trapping (CPT) is widely used to simply produce narrow atomic resonances below 100 Hz in a three-level atomic system with buffer gas. The interrogation method usually involves continuous interrogation of the atoms with two coherent laser fields which couple two ground states to a common excited state (Fig. 1).

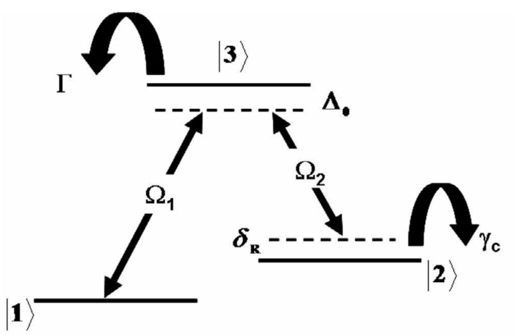

Fig. 1. Three level system interacting with two resonant coherent laser fields with Ω_1 and Ω_2 Rabi frequencies. Δ_0 is the common optical detuning and δ_R is the Raman detuning in microwave domain. Γ and γ_c are respectively spontaneous emission and hyperfine coherence relaxation terms.

When the Raman resonance condition $\delta_R = 0$ is fulfilled, the CPT phenomenon arises, leading to a cancelation of both the fluorescence and the absorption due to destructive interference between amplitudes of transition in the two optical pumping channels. In the first part of this paper, we point out the difference between two polarization configurations : the conventional Λ configuration using two parallel circularly polarized laser beams, and the $\Lambda\Lambda$ configuration using crossed linear polarizations. Then, the CPT pulsed interrogation method is described and the optimization of the time sequence is presented. Finally, the result of a very preliminary frequency stability measurement is shown, demonstrating the potentiality of the proposed technique.

II. Λ VERSUS $\Lambda\Lambda$ POLARIZATION CONFIGURATIONS

Our experimental set-up has been presented previously [1]. Two monochromatic phase-coherent laser beams tuned to Cs-D1 pumping transitions provide independent adjustment of frequency, intensity and polarization for each beam. Both beams are superposed on a polarizing beam splitter cube. One output provides the reference beat note at 9.2 GHz, and the other is sent to the atomic cell through an acousto-optical modulator. The cell at room temperature is filled with cesium vapor with 23 torr N_2 buffer gas. A 20 μT longitudinal static magnetic field is created by a surrounding solenoid and the whole physics package is magnetically shielded. With orthogonal linear polarizations, the laser beams parallel to the magnetic field make a $\Lambda\Lambda$ or lin-per-lin optical configuration. The main advantage is the reduction of optical pumping processes towards the end Zeeman sub-levels. The consequences are (1) the better symmetry of the microwave spectrum, reducing Rabi pulling effects and (2) the increase of of the central fringe contrast (Fig. 2).

The influence of the laser intensity on the central fringe contrast is shown on Fig. 3 for the two polarization configurations. We observe that the contrast continuously increases with the laser intensity for $\Lambda\Lambda$ configuration and reaches values larger than 10%. For Λ configuration, the contrast reaches a lower value (2.5%) and then decreases to 0 due to optical pumping effects.

III. PULSED CPT INTERROGATION

To get clock signals with narrow linewidths, two approaches are possible. On one hand, continuous CPT interaction can be used at low laser intensity, since the width of this resonance linearly decreases with the intensity, but eventually leads to a poor SNR. On the other hand, inspired from earlier work [2], pulsed CPT interaction at high laser intensity can give good SNR with linewidths which no longer depend on laser intensity but scale as $1/(2T)$ where T is the free evolution time between the two pulses. In our experiment, the pulsed CPT interrogation is achieved with an optical preparation pulse during τ followed by a free evolution time T in the dark. The measurement of the absorption signal is performed at a time τ_m during the application of another light pulse of duration τ (Fig. 4).

This sequence is almost equivalent to the usual Ramsey sequence and leads to fringe widths independent of the laser intensity. By combining the lin-per-lin polarizations with the pulsed CPT method, high contrast and narrow width signals can be recorded as in Fig. 5. In particular, the 500 Hz wide

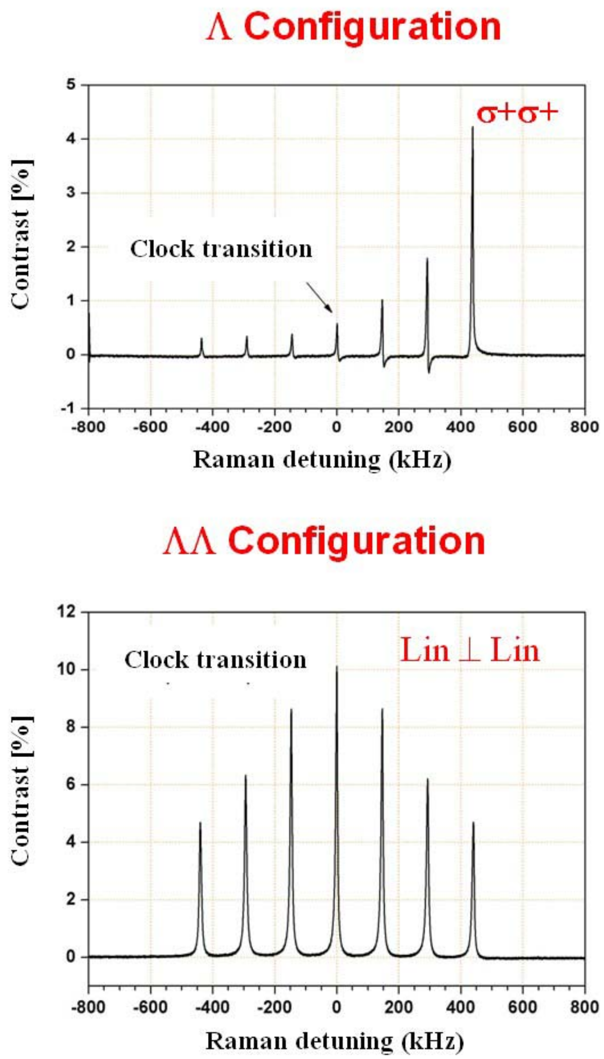

Fig. 2. CPT spectra obtained with Λ and $\Lambda\Lambda$ polarization configurations.

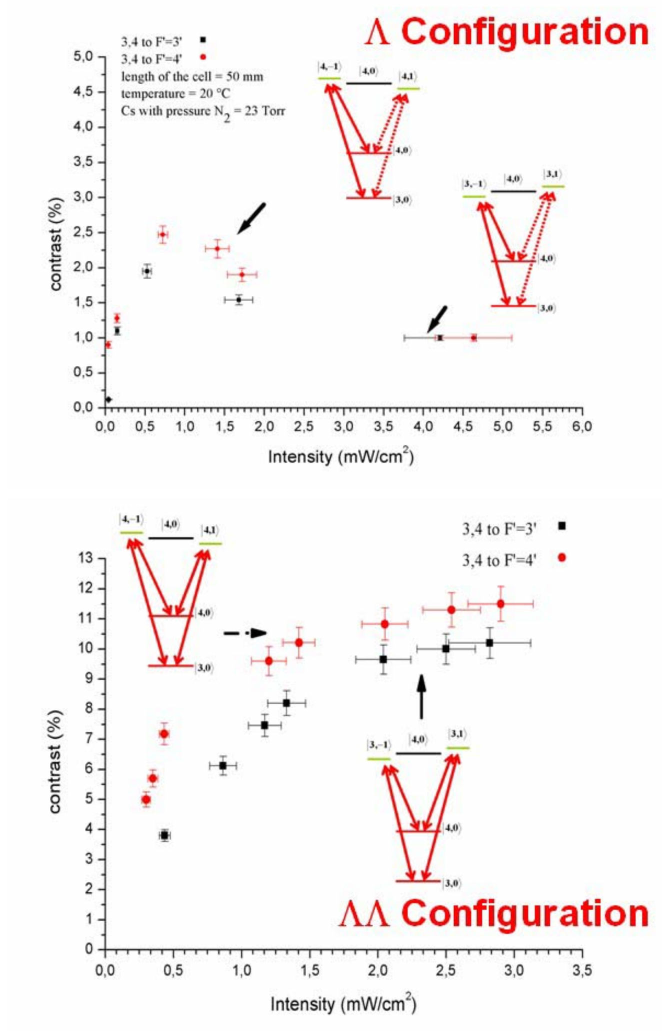

Fig. 3. CPT central fringe contrast obtained with Λ and $\Lambda\Lambda$ polarization configurations. Plain black squares are used for Λ systems to upper $F' = 3$ common levels and plain red circles to upper $F' = 4$ common levels.

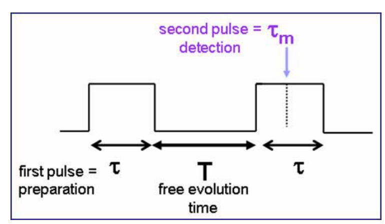

Fig. 4. The pulse time sequence (τ, τ_m, T) used to prepare and probe the CPT signals avoids the limitations due to optical saturation.

central fringe focus in Fig. 6 corresponds to $T = 1$ ms free evolution time.

However there are few difference between this pulsed CPT interrogation technique and the Ramsey technique. In our case, the measurement is done during the second pulse and not after it. It means that is is possible to perform the detection without any perturbation of the atomic state. Moreover, we are in a special interaction regime associated to the relaxation of the coherence during the interaction (especially due to saturation effects. During each interaction with the laser beams, the atomic state reaches a stationary state which is the same as the one obtained for a continuous operation. As a consequence, the observation of the fringes will critically depend on the choice of the measurement time τ_m : they can be observed only if the detection is done during the transient evolution of the atomic state. In other words, in this transient regime, the oscillating Raman-Ramsey fringes are modulated by the Rabi envelope. Note that τ_m does not affect the fringe width but only the fringe envelope. The fringe width is determined only by the free evolution time T. For long τ_m, the atom-laser state evolves to the asymptotic situation where all the atoms are trapped in the dark state. In this stationary regime, the Lorentz signal width is determined by optical saturation. Another difference with Ramsey technique is that it is possible

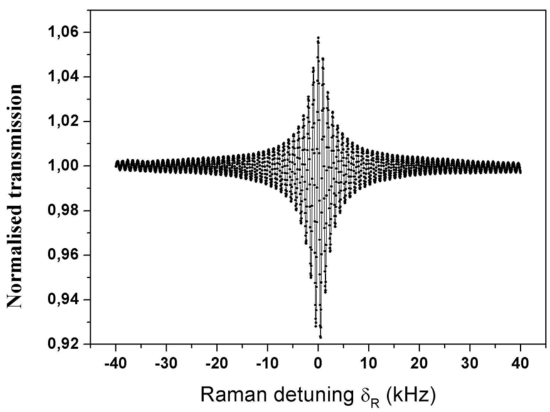

Fig. 5. Experimental saturated Raman-Ramsey fringes obtained with 5 ms preparation time and 5 μs measurement time. The total laser intensity 500 μW/cm^2.

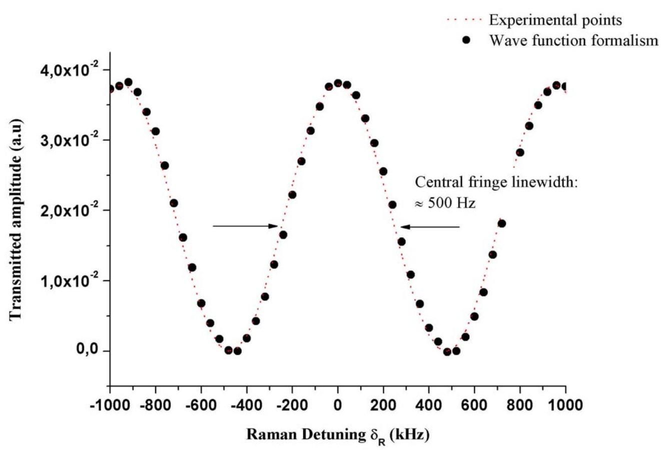

Fig. 6. The 500 Hz central fringe width corresponds to $T = 1$ ms free evolution time.

to interrogate the atoms not with a pair of pulses but with a long series of pulses. In this case, each pulse will be used both for detection and preparation of the atomic state :

- the atomic state which has been prepared by the previous pulse is detected at the beginning of the considered pulse
- a new atomic state is prepared during the considered pulse and will be detected at the beginning of the next one

IV. Time sequence optimization

To optimize the pulse sequence (τ, τ_m, T), the central fringe contrast is measured separately as a function of the three durations in the sequence. The Raman-Ramsey signal can be written as the product of a function only depending on the interaction times $F(\tau, \tau_m)$ by the oscillating fringe factor which is exponentially damped:

$$F(\tau, \tau_m)\left[1 - e^{(-\gamma_c T)} \cos\left(\delta_R T + \Delta\phi\right)\right]$$

In Fig. 7 the experimental central fringe contrast is plotted versus the preparation time τ.

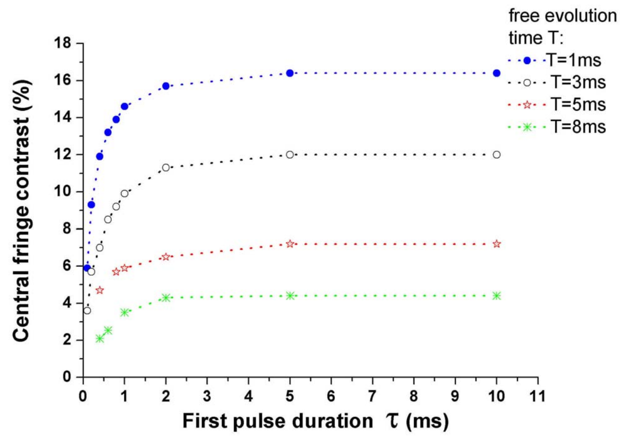

Fig. 7. Central fringe contrast versus the preparation time τ for different values of T. The total laser intensity is 500 μW/cm^2. The optimized sequence needs preparation times longer than 1 ms.

As the preparation time is increased the contrast reaches a maximum. Thus after a typical 3 ms preparation time, atoms are pumped into the dark state. If the free evolution time is increased, the maximum level decreases, as described by the exponential decay factor, but the maximum is still reached after a few milliseconds.

In Fig. 8, the central fringe contrast is plotted versus the measurement time τ_m.

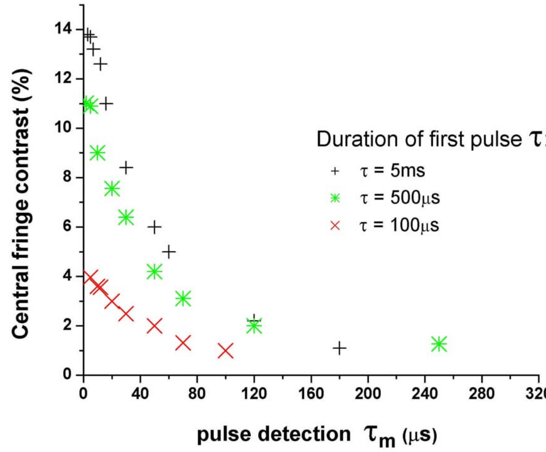

Fig. 8. Central fringe contrast versus the measurement time τ_m for different values of τ. The free evolution time is $T = 1$ ms and the total laser intensity is 500 μW/cm^2. The optimized sequence needs measurement times shorter than 10 μs.

As the measurement time is increased, the contrast rapidly decays to zero. Due to the exponential loss of contrast during the interaction time, the faster the measurement (about 1 μs), the higher the contrast (about 10%). As stated above, the contrast is higher for longer preparation times.

Finally, the central fringe contrast is plotted versus the free evolution time in Fig. 8.

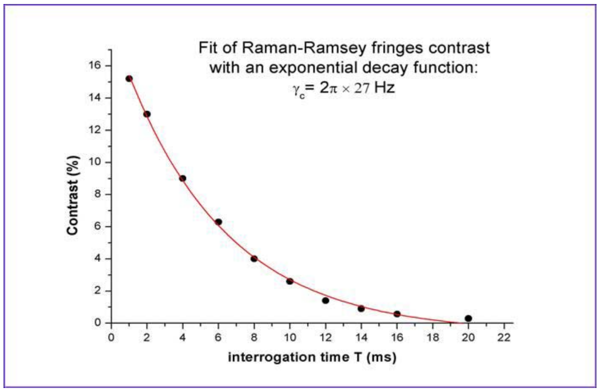

Fig. 9. Central fringe contrast versus the free evolution time T. The hyperfine coherence relaxation in the dark is responsible for the exponential decay. The optimized sequence needs free evolution times shorter than 20 ms.

As the atoms freely evolves during the dark time, the hyperfine coherence is exponentially damped due to relaxation effects in the cell like spin exchange, collisions in the buffer gas and diffusion to the walls. By increasing the free evolution time T, the loss of contrast can be fitted with an exponential decay function. The decay time constant 5.9 ms is a measurement of the coherence lifetime. In our experiment T can take values up to 20 ms, leading to fringes as narrow as 25 Hz.

The experimental optimization of the sequence has been validated by numerical calculations with density matrix formalism [3].

V. Preliminary measurement of the frequency stability

From previous graphs and discussions, the pulsed CPT interrogation sequence is optimized for long preparation pulses and high laser intensities. Resulting experimental fringes are plotted in Fig. 9.

With 5 ms preparation time, the central fringe contrast is 14%. To compare both continuous and pulsed CPT interactions, a figure of merit can be defined as the signal contrast-to-linewidth ratio. It gives the typical slope of the atomic frequency discriminator. We have demonstrated that this ratio is 65 times higher for pulsed CPT than for continuous CPT.

A preliminary measurement of the frequency stability has been done (Fig. 10), showing a Allan deviation of 3.5 10^{-12} tau$^{-1/2}$ on short term. However, this measurement has been done in poor conditions : only one buffer gas leading to a temperature coefficient of 10^{-8} per Kelvin, no thermal stabilization, no signal processing, ... Thus, we consider that there is still room for an noticeable improvement of this stability.

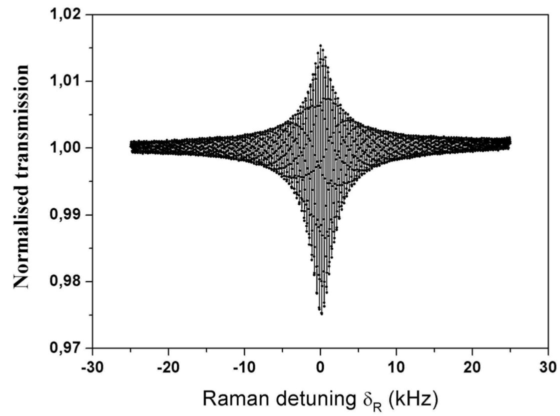

Fig. 10. Experimental Raman-Ramsey fringes obtained with a pulse time sequence optimizing the central fringe contrast-to-linewidth ratio. This time sequence ($\tau = 5$ ms, $\tau_m = 10$ μs, $T = 3$ ms) generates a 166 Hz wide central fringe with 14% contrast.

VI. Conclusion

CPT pulses with crossed linear laser polarizations provide high contrast Raman-Ramsey fringes (more than 10%) with small linewidths (a few tens of Hz). The pulse sequence is optimized for long preparation time (5 ms), high laser intensities (a few μW/cm^2) and very short measurement time in order to saturate the Raman process. This leads to a frequency stability of 3.5 10^{-12} tau$^{-1/2}$ which should be improved in a near future.

VII. Conclusion

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