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REALIZATION OF A CPT RB MASER PROTOTYPE FOR GALILEO

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Abstract – **In this paper we report the realization of a CPT Rb maser clock. This study is devoted to test the stability performances of this new clock, having in mind the requirements of the Galileo navigation system. In the paper the project choices will be discussed, with regard to the physical package and the electronic and optical system. In the last section first experimental data are reported.**

Keywords – **Galileo navigation system, CPT Maser, Frequency standard.**

I. INTRODUCTION

The Coherent Population Trapping phenomenon has drawn a lot of attention in the last years in the time and frequency community. The possibility to observe microwave transition with an indirect excitation through the optical coherences allows to realize completely new frequency standards whose capability have not yet completely investigated.

Several studies have addressed this topics both on the theoretical and the experimental point of view [1-5]. There are basically two different approaches that could be used for the observation of the atomic resonance signal: the first one is the observation of the transmitted laser power (EIT signal [6]), the second one is the direct observation of the coherence through a resonant cavity (CPT maser).

Even if the two systems are based on the same physical principle, these two approaches are fundamentally different in the practical realization, and open different avenues in the project and the exploitation of their metrological capabilities. The principal advantages of the CPT approach rely on a easier control of the light shift, and on higher Signal to Noise ratio with respect to the classical rubidium with lamp or laser pump. At contrary the Dark line approach, with no need of a microwave cavity, allows to reduce the dimensions.

The CPT rubidium Maser prototype we are developing is oriented to study the short and medium term capabilities of this frequency standard (from 1 s to 1 day), having in mind the clock requirements of the Galileo navigation satellite system. A stability of $10^{-12}\tau^{-1/2}$ with a flicker floor of 10^{-14} is our ultimate goal. These performances, if achieved, would be of great interest for the Galileo satellites since are a factor five better than the rubidium frequency standard specifications.

In the following paragraphs the project of a CPT maser will be described focusing the discussion on the choices done in the realization of the system, showing the feasibility of a clock with the above mentioned stability performances.

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THE CPT MASER PHENOMENA

The theory of the CPT maser was studied in depth in [7-9] hereafter only a short introduction is reported for the reader convenience.

The phenomenon of Coherent Population Trapping (CPT) can be observed in alkali-metal atoms when the two ground-state hyperfine levels are coupled to a common excited state, typically the P state, by means of two coherent laser radiations (Λ scheme, see figure 1) [10]. When the frequency difference of the two applied fields becomes equal to the hyperfine splitting of the ground-state levels (6.834 GHz for ^{87}Rb), a resonant mechanism takes place. The atoms are trapped in a coherent state where they are no longer able to absorb energy from the lasers. This trapping mechanism is responsible for the creation of a dark state in the ensemble, causing a dark line in the fluorescence spectrum [11]. Moreover, due to the oscillating magnetization created in the atomic ensemble by the strong coherence generated by the Λ excitation scheme, coherent microwave emission at the ground state hyperfine frequency is observed when the atoms are placed in a microwave cavity. This coherent microwave radiation can be used in the implementation of the CPT maser.

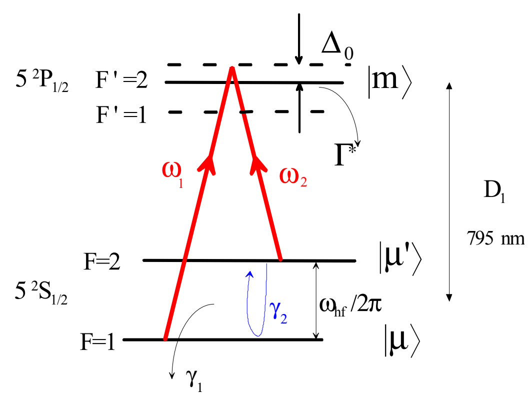

Figure 1 – Atomic levels of interest for the CPT maser. Δ_0 is the laser detuning from the optical transition.

This simple theoretical approach, even if can give a lot of useful information about the atomic system, is somehow misleading when used for the project and realization of a clock prototype. Since it does not take into account important phenomena like the atomic feedback and the effects related to the atomic density, its predictions are loosely descriptive of the real behavior. The introduction of the atomic density, of the medium length and of the cavity feedback on the atoms, leads to a much more complex system of non linear differential equation derived in [9] and hereafter reported.

$$\begin{cases} \dfrac{\partial \Delta}{\partial t}+\left(\gamma_1+\dfrac{\omega_{R1}^2+\omega_{R2}^2}{2\,\Gamma^*}\right)\Delta=-2\ \mathrm{Im}\left(\tilde{b}^*\,\delta_{\mu\mu'}\right)+\dfrac{\omega_{R1}^2-\omega_{R2}^2}{2\,\Gamma^*} \\ \dfrac{\partial \delta_{\mu\mu'}}{\partial t}+\left[\gamma_2+\dfrac{\omega_{R1}^2+\omega_{R2}^2}{2\,\Gamma^*}+i\left(\Omega_\mu+\dfrac{\partial(\phi_1-\phi_2)}{\partial t}\right)\right]\delta_{\mu\mu'}=i\,\dfrac{\tilde{b}}{2}\,\Delta-\dfrac{\omega_{R1}\,\omega_{R2}}{2\,\Gamma^*} \\ \dfrac{\partial \omega_{R1}}{\partial z}+\dfrac{1}{c}\dfrac{\partial \omega_{R1}}{\partial t}=-\dfrac{\alpha}{2\,\Gamma^*}\left[\omega_{R1}(1-\Delta)+2\,\omega_{R2}\ \mathrm{Re}\,\delta_{\mu\mu'}\right] \\ \dfrac{\partial \omega_{R2}}{\partial z}+\dfrac{1}{c}\dfrac{\partial \omega_{R2}}{\partial t}=-\dfrac{\alpha}{2\,\Gamma^*}\left[\omega_{R2}(1+\Delta)+2\,\omega_{R1}\ \mathrm{Re}\,\delta_{\mu\mu'}\right] \\ \dfrac{\partial(\phi_1-\phi_2)}{\partial z}+\dfrac{1}{c}\dfrac{\partial(\phi_1-\phi_2)}{\partial t}=-\dfrac{\alpha}{\Gamma^*}\left(\dfrac{\omega_{R2}}{\omega_{R1}}+\dfrac{\omega_{R1}}{\omega_{R2}}\right)\mathrm{Im}\,\delta_{\mu\mu'} \\ \tilde{b}=-2\,i\,e^{i\psi}\,\dfrac{k}{L}\displaystyle\int_0^L \delta_{\mu\mu'}\,e^{-2i\pi z/\lambda}\,e^{i(\phi_1-\phi_2)}\,dz \end{cases} \qquad (1)$$

where we have defined Δ the ground state population difference, γ_1 and γ_2 the relaxation rates of the ground state population difference and coherence respectively, Γ^* the excited state relaxation rate, ω_{R1} and ω_{R2} the two optical Rabi angular frequencies, $\delta_{\mu\mu'}$ the ground state coherence, Ω_μ the microwave detuning, ϕ_1 and ϕ_2 the laser phases, λ the microwave wavelength (4.4 cm for ^{87}Rb), α the absorption coefficient, ψ the cavity detuning parameter and $\tilde{b}$ the complex microwave Rabi frequency. To obtain (1) we have assumed the rotating wave approximation for the coherence terms and the slowly varying approximation for the amplitudes and the phases of the optical fields.

The system (1) can be analytically solved only in a limited number of particular cases, but numerical solutions, upon variation of various parameters, can be easily found.
The principal effects we could highlight from the analysis of the above system are reported hereafter.

1) Propagation shift: this shift is caused by the phase variation of the two laser beams frequency difference s along the quartz cell; since each atomic slice experience a different light field the overall magnetization phase will be a function of the cell length.
2) Microwave shift: the microwave emitted produces a feedback on the atoms that stimulates microwave emission further, this creates an unbalance in the population of the ground state levels, that in turn produces a frequency shift.
3) Density effects: the atomic density produces several effects, the most important for the CPT Maser project is the linewidth narrowing, respect to the low density approximation. However the absorption of the laser field along the cell produces strong correlation between the temperature of the atoms and various other shift effects like microwave and propagation shift.

The CPT maser prototype we are developing at IEN is essentially composed of four main parts (figure 2): Optical system, Physical Package, RF and DC Electronics, digital electronic.

Optical system. The optical system provides the lasers fields required to excite the Λ transition. An extended cavity laser diode (≈8 mW at the laser head) is coupled to an electro-optic phase modulator (EOM) by single mode polarization maintaining optical fibers that allow a precise control of the beam polarization. Applying to the EOM the output of a microwave synthesizer at 3.4 GHz and tuning the laser to the D_1 line center of gravity, the first two sidebands of the output spectrum provide the two optical frequencies required to the Λ excitation scheme.
The use of an EOM assures to high level the phase coherence between the two optical fields, and strongly reduces the sideband asymmetry due to the superposition between amplitude and frequency modulation unavoidable when the modulation is applied to the laser current. The spectrum symmetry is necessary if we want to compensate the amplitude light shift with applying a given phase modulation index to the laser carrier [12, 13].

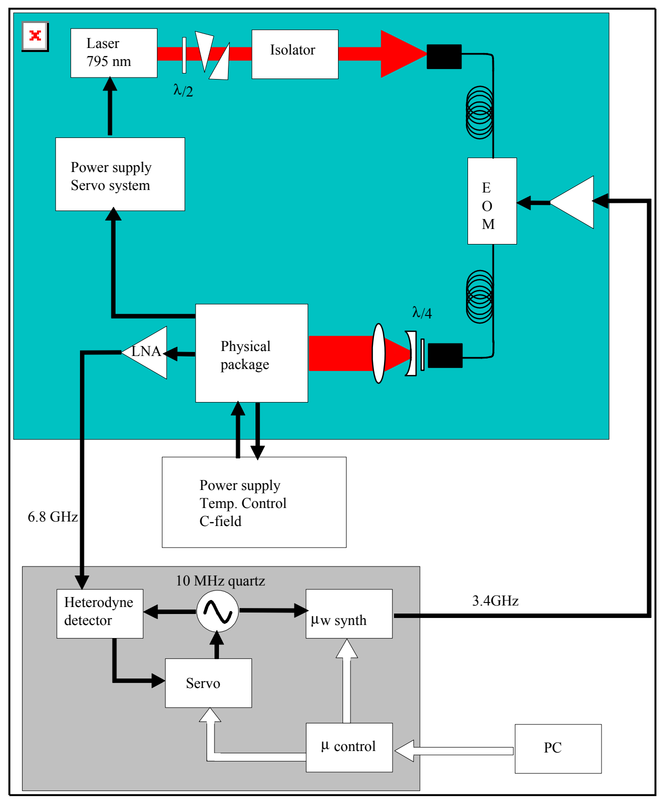

Figure 2 – Scheme of the CPT maser prototype.

The laser beam is circularly polarized by means of a $\lambda/4$ wave plate is expanded to 2 cm diameter and is sent to the physical package. An optical power of 1 mW, with a modulation index of 4, is experimentally achieved with our phase modulator, while in the operating condition 300μW of light, with a phase modulation index around 2.4 are close to optimum.

<u>Physical package.</u> The core of the physical package is the quartz cell and the cavity. The cell contains the ^{87}Rb atoms and a mixture of buffer gases, as discussed later on. The physical package also includes a solenoid providing the C-field, a double magnetic shield to reduce environment magnetic field fluctuations and to control the temperature at the level of 1mK.
The cell contains the ^{87}Rb atoms and a mixture of buffer gas. It is made in quartz, not to affect the quality factor of the cavity. Being the microwave wavelength of the clock transition λ = 4.4 cm, the cell has been designed with L = 2.2 cm, in order to minimize the propagation shift and to maximize the emitted power [7, 9].
The cavity is made in copper and is cylindrical. It resonates at the hyperfine frequency (6.834 GHz) on the TE_{011} mode. This mode assures a good coupling between the field sustained by the cavity and the magnetization created by the atoms. Moreover, this mode guarantees a high Q_L also when the cavity contains the cell. In this regard, we observe that the CPT maser does not require a cavity quality factor particularly high, since there is no threshold for the coherent emission. However, a high Q_L assures a high signal-to-noise ratio, without being necessary to increase the atomic density. In our case, we have $Q_L \approx 7000$.
The cavity is frequency tuned with the cell inserted inside for an operating temperature between 60 and 65 °C. A nylon screw is used for fine tune the cavity with the maser in operation. The screw, by changing the dielectric property of the medium, allows a frequency tuning of few MHz.

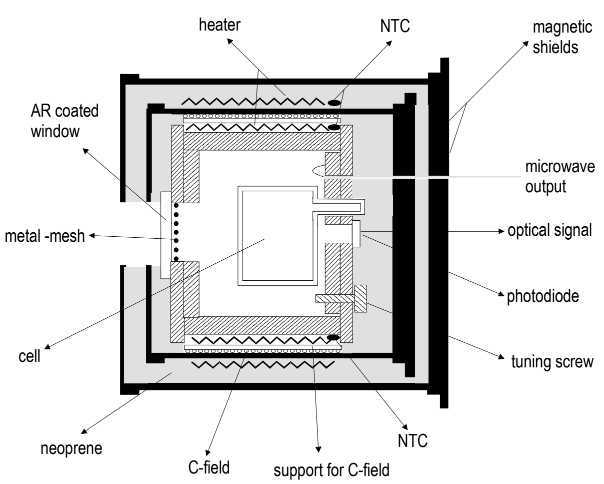

Figure 3 – Physical package.

A fundamental point in the project of the maser is to find the right working temperature, where none of the temperature dependent shifts become critical, but also where the signal is sufficiently high.
At a temperature of 60-65 °C, the linewidth narrowing observed on the emission profile is already significant, while the non linear effects related to the atomic density are not yet destructive. The corresponding atomic density is n = 3x10^{11} cm^{-3} and for L = 2.2 cm the optical length of the cell turns out to be $\zeta \approx 3.5$. At this temperature and for our buffer gas composition the population and the coherence decay rates (γ_1 and γ_2 respectively) are both of the order of 300 s^{-1}. With a buffer gas total pressure of 25 Torr ($P(Ar)/P(N_2)$ =1.6) we have $\Gamma^* = 3\times10^9$ s^{-1} [14].
Table 1 lists the main parameters of the physical package.

Cavity Dimensions L f	L 40 x f 52 mm
Resonance Frequency	6.834 GHz
Loaded Quality Factor	7000
Tunability	200 kHz/turn
Cavity Coupling (b)	> .35
Magnetic Shield Factor	100
Temperature Sensititvity	100 kHz/K
Cell Dimensions L f	L 25 x f 31 mm
Buffer Gas Mixture	$P(Ar)/P(N_2)$ =1.6
Filling Factor (h¢)	>.28
Cavity working Temperature	55-65 °C
Heating Power (cavity)	» 3 W
Shield working Temperature	45-55 °C
Heating Power (shield)	» 3 W
Thermal Constant (cavity)	> 3400 s

Table 1 – Summary of the physical package characterization.

<u>Electronic apparatus.</u> The set-up is completed by electronics to detect and to generate all the involved signals (see figure 4). In particular, the CPT maser emission is detected by a heterodyne detector and a microwave synthesizer driven by a stable quartz oscillator is used to modulate, by means of the EOM, the phase of the laser carrier. The low frequency electronic has the task to frequency lock the laser to the D_1 center of gravity via the optical signal and to stabilize the temperature of the physical package.

<u>Digital control unit and PC user interface.</u> This part provides a digital control of the whole electronics. It is composed of a Micro-Controller (μC) and of a Programmable Logic Device (PLD). It controls frequency offset with proper resolution, kind of modulation and related parameters, such as frequency modulation, modulation depth, etc. required to lock the quartz oscillator to the clock transition. The user can set these parameters by computer.

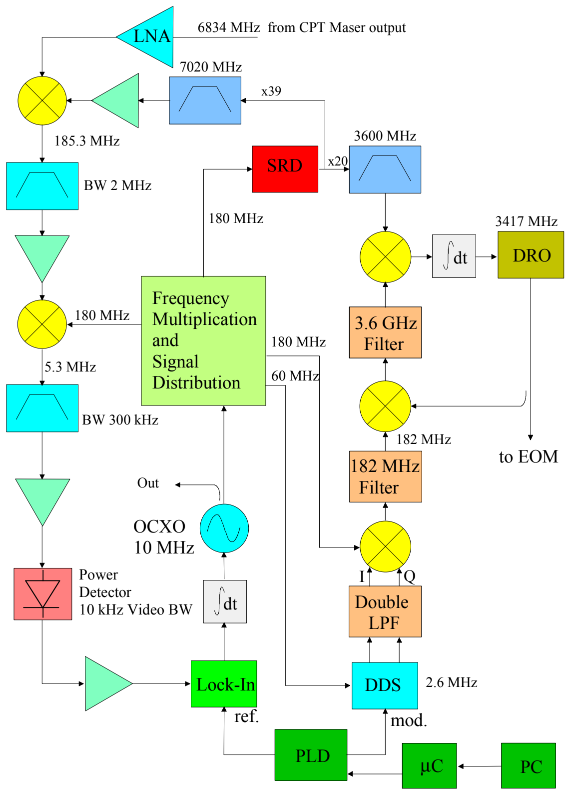

Figure 4 – Synthesis and detection chains.

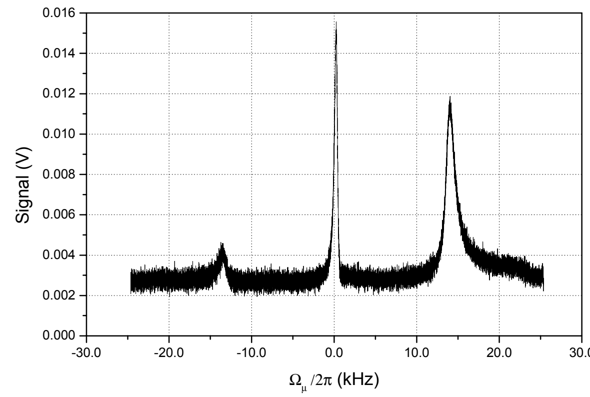

Figure 5 –Transmission signal.

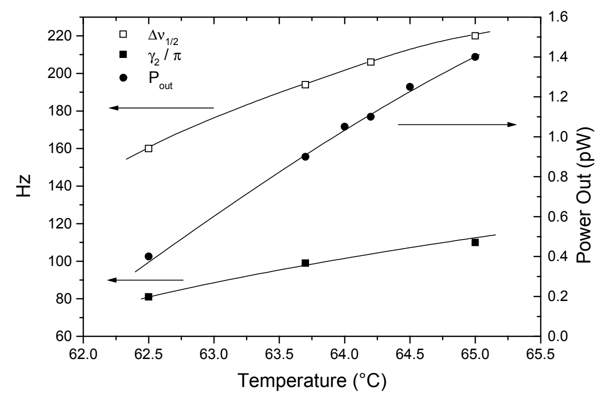

Figure 6–Linewidth (white square), coherence relaxation rate (black squares) and output power of the CPT maser vs temperature.

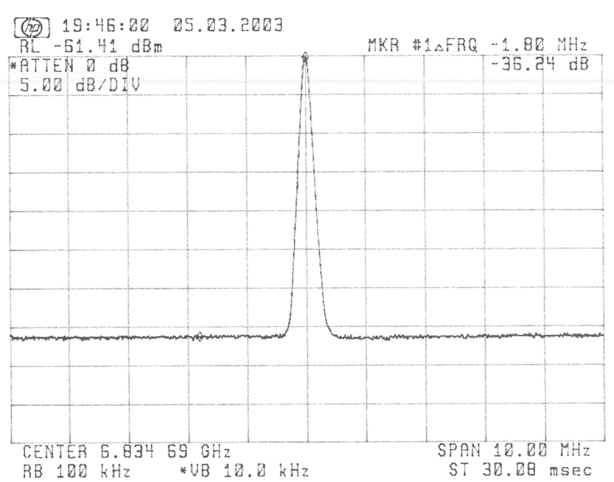

Figure 7 –CPT maser RF spectrum.

PRELIMINARY EXPERIMENTAL DATA

At the time of the conference we are still assembling the final version of the electronic that is required to rally test the better stability performances. However we have done a preliminary experimental characterization of the system with regard to various parameters.

The magnetic field homogeneity obtained with the double shield is good enough to be able to operate the standard at relatively low field (in figure 5 a field of 10 mG is applied), reducing then the sensitivity to external magnetic field fluctuation. As can be observed, the broadening of the magnetic sensitive lines is evident but does not affect the resolution of the clock transition.

Figure 6 shows the linewidth of the emission profile and the output power versus temperature. In particular, for a working temperature of 64 °C the linewidth is about 200 Hz and the emitted power is more than 1 pW. The behavior of the coherence relaxation rate (γ_2/π) is also shown.

When we observe the maser signal at the output of the heterodyne detector a signal to noise of $2x10^4$ is obtained for a bandwidth of 1 Hz using a low noise amplifier with 1 dB of noise figure (see figure 7).

This value with a measured linewidth of ≈ 200 Hz (Q_a = $3x10^7$) allows to reach a short term stability of $1x10^{-12}\ \tau^{-1/2}$.

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