CPT Atomic Clock based on Rubidium 85

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Abstract - We present a compact physics package based on coherent population trapping (CPT) in rubidium 85. The architecture of the package is described along with results obtained using optical- and microwave spectroscopy. We also report the stability of the CPT resonance to variations in operating parameters such as microwave modulation power and vapour cell temperature. With this package we obtain a short term frequency stability $\sigma_y(\tau) = 7\cdot10^{-11}\cdot\tau^{-1/2}$ ($\tau < 100$ sec) and $\sigma_y(\tau) \sim 1\cdot10^{-11}$ (100 sec $< \tau < 10^4$ sec).

1. INTRODUCTION

Today the majority of commercial frequency standards are based on rubidium clock technology [1]. This technology uses optical pumping to prepare and detect the hyperfine ground state of rubidium atoms in a vapour cell. When the frequency of a microwave field is swept across the rubidium hyperfine resonance a dip in the cell transmission appears. The dip serves as a frequency marker to which one can lock a voltage controlled oscillator. In locked mode the intrinsic stability of the atomic resonance and low sensitivity to environmental perturbations is transferred to the oscillator and available to the end user. Rubidium clocks are used to synchronize the time base in telecom networks, power grids, and satellite navigation systems such as GPS and Galileo.

Coherent population trapping (CPT) provides an alternative method to detect the rubidium clock resonance. With this method both hyperfine ground states are coupled to an excited state by two optical radiation fields in a Λ-scheme configuration [2]. When the relative detuning between the optical fields is swept across the resonance, atoms are pumped into a coherent "dark" state and a dip in the cell absorption appears. This effect, observed in sodium atoms using a multimode dye laser, was reported for the first time in [3]. A simple and compact scheme for a CPT atomic clock was proposed in [4] using two sidebands of a modulated laser separated in frequency by the atomic resonance. The use of this simple CPT scheme in a commercial product has so far been blocked by the lack of reliable and low cost laser sources at the proper wavelength. However, the recent advent of vertical cavity surface emitting lasers (VCSEL) with single mode emission, stable polarization output, and high modulation bandwidth has removed this obstacle. As a result first reports on industrial rubidium CPT clocks have been published by Kernco [5] and Symmetricom [6]. In addition, CPT with a modulated VCSEL has been used to realize chip-scale atomic clocks [7-8].

This paper presents a compact CPT physics package based on rubidium 85. In contrast to the reports in [5,6] which use vapour cells with pure or enriched rubidium 87, we investigate the use of vapour cells filled with natural rubidium (~ 70 percent abundance of the rubidium 85 isotope). The advantage of this approach is a simple and cost effective cell fabrication. In the following sections we first present the architecture of the physics package together with optical- and CPT absorption spectra. Next, we discuss the frequency stability of the package to changes in operating parameters such as the microwave modulation power or the vapour cell temperature. Finally we report the frequency stability (Allan deviation) of a laboratory oscillator locked to our physics package.

2. CPT PHYSICS PACKAGE

2.1. Physics Package Architecture

The schematic of the physics package is shown in Fig. 1. The VCSEL emits light close to the 795 nm D1 line in rubidium. To tune the wavelength to this line we heat the VCSEL with a resistive element placed in a feedback loop. The diverging laser beam passes a neutral density filter and quarter-wave plate where it is attenuated and circular polarized, respectively. Finally, the beam enters a glass blown rubidium vapour cell where a photo detector placed after

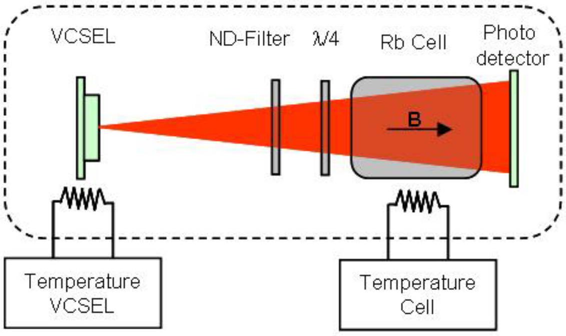

Fig. 1. Diagram showing the parts of the physics package.

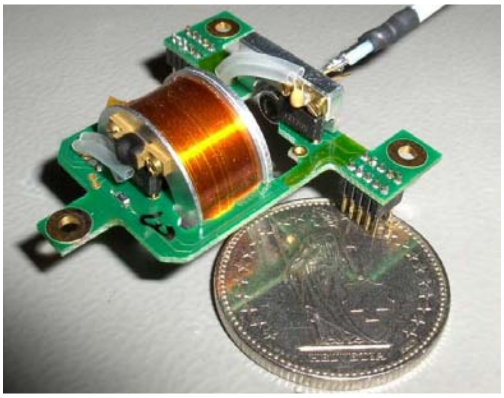

Fig. 2. Photo of the physics package with the magnetic shield removed.

the cell monitors the transmitted light. To increase the absorption on the D1 line we heat the vapour cell with a resistive element. Furthermore the cell is placed at the center of a solenoid which generates a magnetic field B parallel to the optical axis. All parts of the package fit inside a cylindrical magnetic shield with diameter 2.54 mm and length 30 mm. A photograph of the physics package with the magnetic shield removed is shown in Fig. 2.

2.2. Optical Absorption Spectrum

The normalized optical absorption spectrum on the 795 nm rubidium D1 line is shown in Fig. 3. The spectrum is composed of four absorption lines between the different hyperfine ground states in rubidium and the unresolved excited state. Since the vapour cell is filled with natural rubidium the two strongest lines separated by 3 GHz correspond to absorption in the 85Rb isotope. Besides rubidium, the cell is filled with a small amount of buffer gas which leads to a broadening of the optical spectrum due to collisions between rubidium and buffer gas atoms. In addition, these collisions increase the diffusion time of rubidium atoms out of the laser beam which leads to a narrowing of the CPT resonance.

2.3. Microwave CPT Resonance

To observe the CPT resonance we first modulate the VCSEL current at 3 GHz to create coherent sidebands separated from the carrier by a frequency interval equal to the clock transition in 85Rb. Next, we use a feedback loop on the VCSEL DC current to lock the carrier frequency to the F=3 absorption line in Fig. 3. Finally, we sweep the modulation frequency across the 85Rb clock transition and monitor the DC transmitted light level on the photo detector. A plot of the photo detector signal versus the sweep in microwave modulation frequency is shown in Fig. 4. The linewidth of the CPT resonance in Fig. 4 is 1.7 kHz and the contrast is 1.8 %.

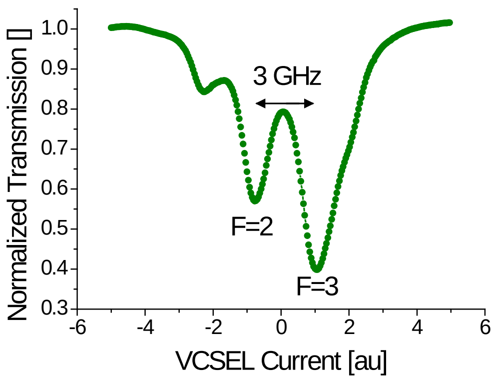

Fig. 3. Optical absorption spectrum. The vapour cell is filled with natural rubidium and buffer gas

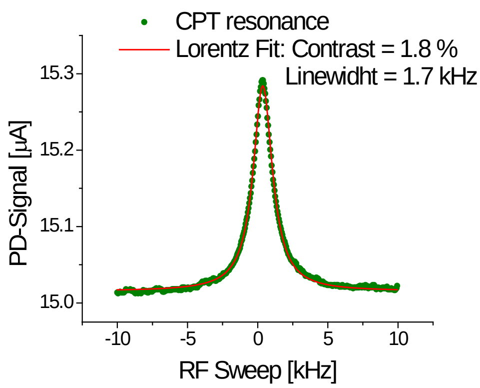

Fig. 4. CPT resonance recorded with the physics package in Fig. 2.

3. STABILITY COEFFICIENTS

The long term frequency stability of an oscillator locked to the physics package will depend on the sensitivity of the CPT resonance position to changes in operating parameters and the level to which these parameters are stabilized. To measure the sensitivity we lock the 3 GHz signal from a laboratory signal generator to the 85Rb resonance and compare it against a hydrogen maser. In Fig. 5 and Fig. 6 we plot the resonance position as a function of microwave modulation power and cell temperature, respectively. In both cases the data are fitted with a 2. order polynomial and the stability coefficient is derived from the tangent to the parabolic curve. Table 1 summarizes the measured stability coefficients.

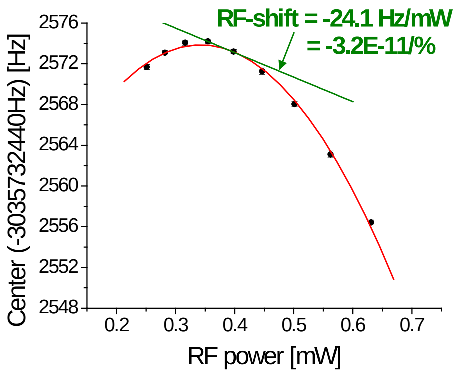

Fig. 5. CPT resonance position measured for different values of the microwave modulation power.

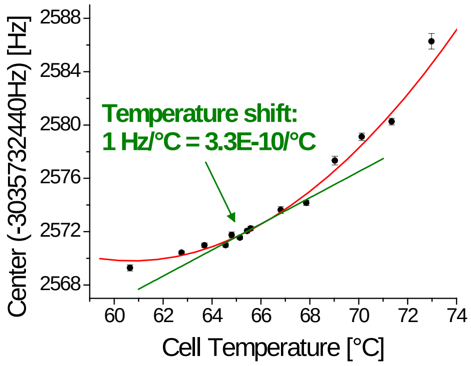

Fig. 6. CPT resonance position measured for different values of the vapour cell temperature

4. FREQUENCY STABILITY

To measure the short term stability we record the frequency fluctuations of the locked signal generator against the hydrogen maser. The Allan deviation of the measured frequency fluctuations is reported in Fig. 7. For integration times $\tau < 100$ seconds the fluctuations are white and we obtain a deviation $\sigma_y(\tau) = 7 \cdot 10^{-11} \cdot \tau^{-1/2}$. In comparison, we predict a short-term stability of $2 \cdot 10^{-11}$ at one second using the measured signal-to-noise ratio and resonance linewidth. For integration times between 100 and 10^4 seconds flicker noise and drift limit the Allan deviation at a level just below 10^{-11}. Work is in progress to improve the long term stability and keep the deviation below 10^{-11} over one day of integration.

Table 1. Stability coefficients measured using the setup and data analysis shown in Fig. 5- Fig. 7. The operating point of the physics package is: cell temperature = 65.7 °C, RF modulation power = -4 dBm, optical power =28 uW, and magnetic field = 21.7 uT.

Parameter	Fractional stability
Light intensity	7.0E-12/%
Cell temperature	3.3E-10/°C
RF power	-3.2E-11/%
Light frequency	1.3E-11/MHz
Magnetic field	4.0E-10/%

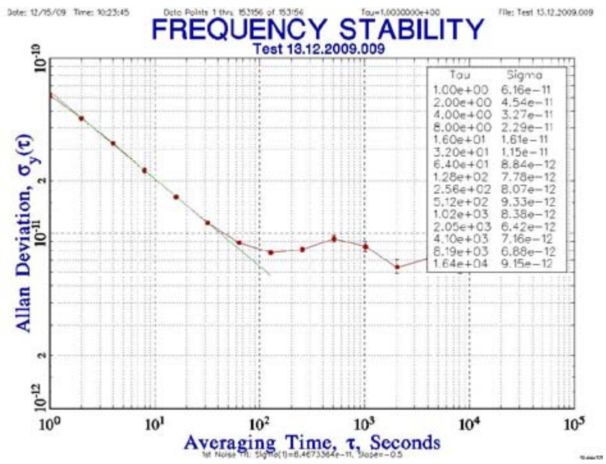

Fig. 7. Allan deviation measured with the CPT physics package of Fig. 2. The “thermal bump” around 500 seconds is due to a periodic variation of the temperature in the laboratory during the measurement.

5. CONCLUSION

We have fabricated and tested a compact physics package based on CPT in the rubidium 85 isotope. The main parts of the package include a commercial available 795nm VCSEL and a miniature glass blown vapour cell. In contrast to previous work that used pure (or enriched) rubidium 87, we fill the vapour cell with natural rubidium. This solution is simpler and more cost effective. For integration times $\tau < 100$ seconds we measure a frequency Allan deviation $\sigma_y(\tau) = 7\cdot10^{-11}\cdot\tau^{-1/2}$. For longer integration times ($100\ s < \tau < 10^4\ s$) this deviation remains close to the 10^{-11} level. Besides frequency stability, we have measured the sensitivity of the CPT resonance to changes in external parameters such as microwave modulation power and cell temperature (Table 1). Work is in progress to demonstrate frequency stability at the level of 10^{-11} for one day of integration. This goal will be achieved by further reducing the sensitivity of the CPT resonance to external parameters and integrating a complete electronics package.

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