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Characterization of compact CPT Clocks based on a Cs-Ne microcell

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Résumé—This paper reports the characterization of compact Cs CPT clocks based on a single buffer gas Cs-Ne microcell. Two different experimental set-ups are tested. The first set-up uses an externally-modulated 895 nm Distributed Feedback (DFB) laser source while the second one uses a directly-modulated custom-designed 895 nm Vertical Cavity Surface Emitting Laser (VCSEL) source. Using the DFB set-up, through reduction of the temperature-dependent collisional frequency shift and an active light shift suppression technique, a clock frequency stability of 3.8×10^{-11} at 1 s and greatly better than 10^{-11} at 60000 s is demonstrated. This proves the potential of single buffer gas Cs-Ne microfabricated cells for the development of miniature atomic clocks. Preliminary characterization of CPT resonances are reported with the VCSEL-based setup. It is expected that similar clock stability performances are achievable in this case.

I. INTRODUCTION

The combination of Coherent Population Trapping (CPT) physics [1] and micro electro-mechanical systems (MEMS) allows the development of chip scale atomic clocks (CSAC) [2] exhibiting a volume of a few cm^3 , a power consumption of about 100 mW and a fractional frequency stability better than 10^{-11} at 1 hour and 1 day integration time [3]. Such frequency references, outperforming crystal quartz oscillators over long time scales, are intended to provide excellent base timing for numerous battery-operated applications such as telecommunication networks synchronization, navigation, military systems or even power distribution and underwater sensing. The heart of a miniature atomic clock is a microfabricated cell containing the alkali vapor and a buffer gas atmosphere to operate in the Dicke regime [4]. Pioneering cell fabrication and filling techniques are reported in [5], [6], [7]. Recently, we proposed an original method where the Cs vapor is generated after complete sealing of the cell by local heating of a side-cavity Cs metallic dispenser with a high-power infrared laser source [8], [9]. The presence of buffer gas in the cell induces a temperature-dependent frequency shift of the clock transition. Currently, the dependence on temperature of the clock transition is cancelled at the first order around a so-called inversion temperature by filling the cell with a buffer gas mixture [10], [11]. This technique is widely used in Rb standards. We recently reported the first direct observation of quadratic dependence on temperature of the Cs clock transition around a so-called inversion temperature T_{inv} of about 80°C in presence of a single Ne buffer gas [12]. In such a case,

the inversion temperature was measured to be not dependent on the buffer gas pressure [13]. These results were confirmed by O. Kozlova et al. reporting in a delicate and metrological study the temperature and pressure shift the Cs clock transition in presence of several buffer gases [14]. Cs-Ne cells are then potential simple-configuration efficient candidates to be used at the heart of chip scale atomic clocks.

We report in this article the metrological characterization of CPT-based vapor cell clocks based on a Cs-Ne microfabricated cell. These cylindrical cells present a diameter of 2 mm and a length of 1.4 mm. Two different experimental set-up are implemented. The first one uses a DFB laser source at 894.6 nm on the Cs D_1 line and an external pigtailed electro-optic modulator for the generation of CPT sidebands. Additive advanced noise reduction techniques are developed in this set-up to improve greatly mid and long-term frequency stability performances. The second set-up uses a directly-modulated custom-designed VCSEL prototype at 894.6 nm developed in the frame of the MAC-TFC project [15] by Ulm University. Preliminary key parameters of the clock as well as an estimation of its short-term frequency stability are reported for this setup.

II. DFB SET-UP

A. Experimental set-up

Fig. 1 shows a simplified scheme of the set-up 1.

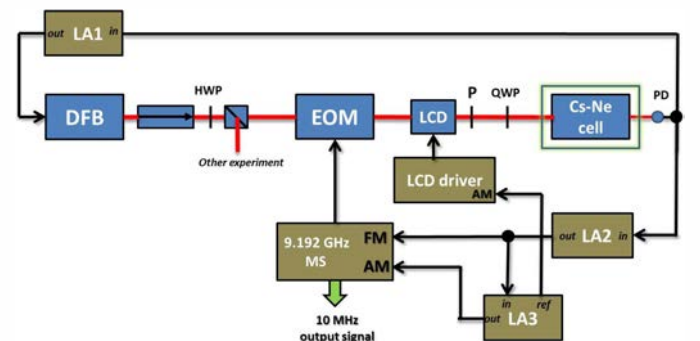


FIGURE 1. Schematic of the Cs-Ne microcell based CPT clock with a DFB laser resonant at 894.6 nm. MS : 10 MHz quartz-oscillator based microwave synthesizer, EOM : electro-optic modulator, LCD : voltage-controlled liquid crystal plate attenuator, P : polarizer, HWP : half-wave plate, QWP : quarter-wave plate, LA1 : lockin amplifier-based servo for laser frequency stabilization through modulation at 60 kHz of the laser bias current, LA2 : lockin amplifier-based servo for locking the local oscillator frequency to the CPT resonance transition, LA3 : lockin amplifier-based servo for light shift correction (LSC).

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The laser source is a commercially-available GaAs semiconductor DFB laser diode emitting at 894.6 nm on the Cs D_1 line.

A Faraday optical isolator is placed at the output of the DFB laser in order to avoid optical feedback. Optical sidebands are generated by driving an external pigtailed phase electro-optic modulator (EOM) at 9.192 GHz using a microwave frequency synthesizer inspired from [16]. No phase noise degradation was observed between the microwave frequency synthesizer output and the 9.192 GHz optically carried signal. The collimated laser beam is circularly polarized using a quarter-wave plate and sent through the atomic cell. The cell temperature T_{cell} is stabilized close to 80°C. Temperature fluctuations of the microcell are below the mK level. A static magnetic field of a few μ T parallel to the laser beam propagation is applied to split the hyperfine ground-state Zeeman transitions. The CPT resonance is monitored by detecting the laser power transmitted through the cell using a low-noise photodiode. The laser is frequency-stabilized near the center of the homogeneously broadened absorption line by modulating the DFB laser current at 60 kHz and demodulating it with the lock-in amplifier LA1. The atomic clock closed-loop operation is achieved by conventional synchronous modulation-demodulation technique (~ 1 kHz frequency) applied to the local oscillator frequency through the lockin amplifier LA2. Light shift is continuously minimized using a method inspired from [17]. For this purpose, the laser power is slowly modulated at 15 Hz (12 % depth) using a voltage-controlled liquid crystal display (LCD) attenuator. This laser power modulation is converted across the cell through the light shift effect into a slight clock frequency modulation that can be easily detected at the error signal output of the lockin amplifier LA2 used to stabilize the LO frequency. This modulation signal is found to be vanished close to a so-called RF power zero-light-point driving the EOM [18], [19]. An additional servo loop based on the lockin amplifier LA3 is eventually added to lock the RF power point where no light shift is present.

B. Experimental results

Fig. 2 shows both the CPT resonance contrast and the clock frequency shift versus the cell temperature. The CPT contrast is maximized in the 74–81°C temperature range. In this temperature range, it is clearly observed that the Cs clock frequency temperature-dependence is cancelled at the first order around 79–80°C. This measurement is in good agreement with [21]. Using coefficients published in [14], a fit of experimental points gives a Ne cell pressure of 79 Torr. This cell allows to make coincide a zero-sensitivity of the clock frequency to temperature variations and a maximum of CPT contrast close to 80°C. This will lead to mutual improvements of the clock long-term and short-term frequency stability. Fig. 3 reports the frequency stability (Allan deviation) of the CPT clock based on a Cs-Ne microcell. It is measured at 10 MHz by comparison with a reference hydrogen maser. The short-term frequency stability is measured to be 3.8×10^{-11} at 1 s. The Allan deviation curve decreases well with a $\tau^{-1/2}$ slope until 1000 s. After 1000 s, the Allan deviation increases again. The frequency stability is greatly lower than 10^{-11} at 60 000 s. These results prove the potential of the Cs-

Ne microcell solution to develop high-performance chip-scale atomic clocks.

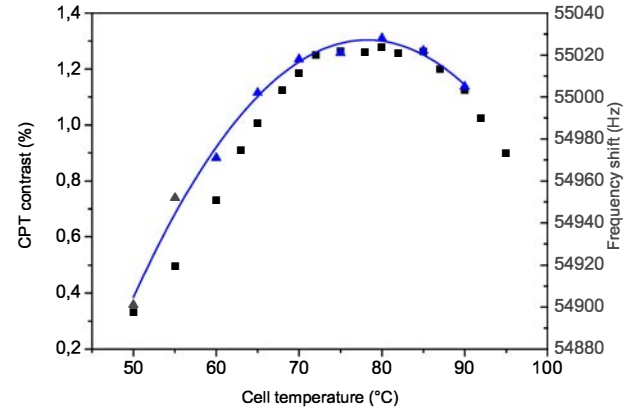


FIGURE 2. CPT resonance contrast (squares) and clock frequency shift (triangles) versus the cell temperature. The solid line is a second order polynomial function fit to the frequency data. For a given temperature, data results from interpolation at zero intensity of light-shift curves. The CPT contrast is found to be optimized close to the clock frequency inversion temperature.

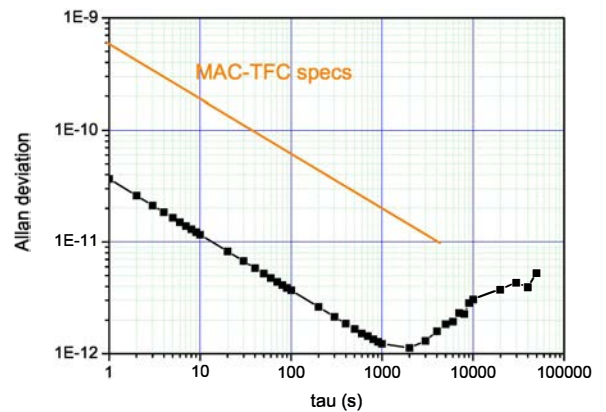


FIGURE 3. Allan deviation of the DFB-based Cs CPT clock. Specifications of the MAC-TFC project are reported for information.

III. VCSEL SET-UP

A. Experimental set-up

Fig. 4 shows a simplified scheme of the set-up 2.

The laser source is a custom-designed VCSEL resonant at 894.6 nm developed by Ulm University [20]. The laser dc current-temperature couple is biased to 1.3 mA - 30°C to be resonant with Cs atom transition D_1 line. The output beam of the laser is collimated into a 2-mm diameter beam and sent across a linear polarizer. The laser power incident to the cell is about 22 μ W. The injection current of the laser is directly modulated at 4.596 GHz with a commercial frequency synthesizer in order to generate two phase-coherent optical sidebands frequency-separated by 9.192 GHz for CPT

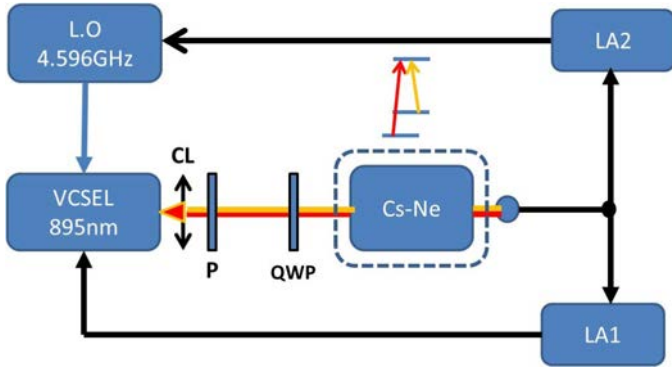


FIGURE 4. Schematic of the Cs-Ne microcell based CPT clock with the custom-designed 894 nm VCSEL. LA1 : lockin amplifier-based servo for laser frequency stabilization through modulation at 60 kHz of the laser bias current, LA2 : lockin amplifier-based servo for locking the local oscillator frequency to the CPT resonance transition. L.O : local oscillator, 10 MHz quartz oscillator multiplied to 4.596 GHz. P : linear polarizer. QWP : quarter-wave plate.

interaction. The RF power incident on the VCSEL is in the $-6 - 0$ dBm range. The Cs cell is filled with 75 Torr of Ne. It is temperature-stabilized, surrounded by a static magnetic field of several μT and placed in a single-layer mu-metal magnetic shield. The laser power is detected at the output of the cell with a photodiode. From this detector is extracted two servo loops. The first one aims to stabilize the laser frequency while the second one is used to stabilize the local oscillator frequency to the atomic hyperfine transition frequency. Up to date, active light shift correction technique has not been implemented in this set-up yet.

B. Preliminary experimental results

Fig. 5 shows the CPT frequency discriminator error signal in the VCSEL-based set-up for a cell temperature of 80°C .

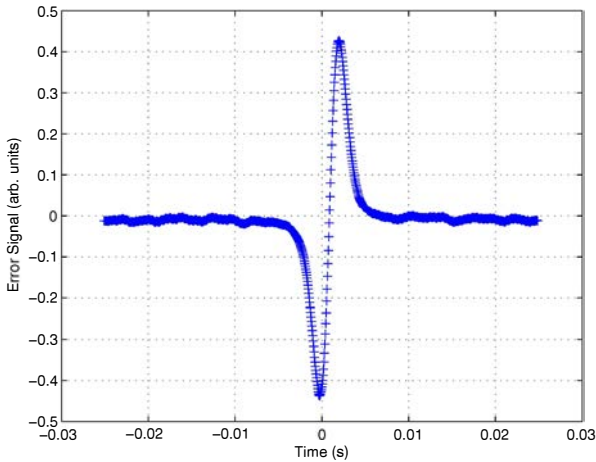


FIGURE 5. CPT frequency discriminator error signal. The slope is 0.9×10^{-6} V/Hz. The cell temperature is 80°C . The RF power is -2 dBm.

The CPT linewidth is measured to be about 1.05 kHz at 80°C and does not vary significantly in the $70-90^\circ\text{C}$ range. The contrast, defined as the ratio between the CPT signal

and the background, is maximized at about 0.95 % at 80°C . The detection noise N in a 1 Hz bandwidth at the LO modulation frequency is $1.7 \times 10^{-7} \text{ V}/\sqrt{\text{Hz}}$. The CPT clock frequency discriminator slope D is typically $0.9 \times 10^{-6} \text{ V/Hz}$. The expected short-term stability of the clock is then expected to be $\sigma_y(\tau) = \frac{1}{\sqrt{2\nu_0 D}} = 2.9 \times 10^{-11}$ at 1 s averaging time at $T = 80^\circ\text{C}$. Frequency stability measurements will be led in a near future.

Fig. 6 reports the CPT contrast versus the 4.6 GHz RF power. The contrast is found to be maximized in the $-2 - -3$ dBm range.

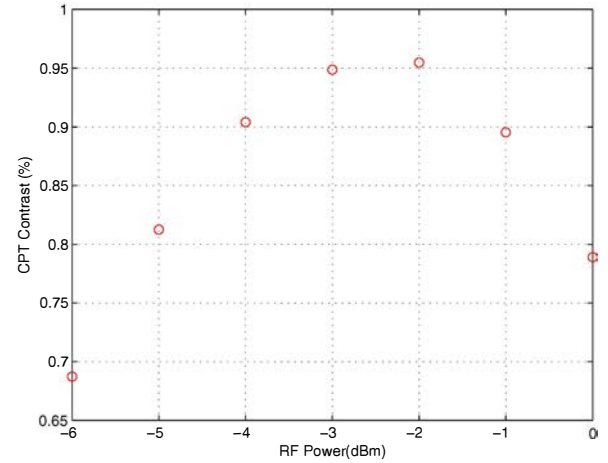


FIGURE 6. CPT resonance contrast versus the 4.6 GHz RF power. The cell temperature is 80°C .

IV. CONCLUSIONS

We developed compact Cs CPT clocks based on a Cs-Ne microfabricated cell. A first clock set-up, using an externally-modulated 894 nm DFB laser, exhibits a typical relative frequency stability of 3.8×10^{-11} and lower than 7×10^{-12} at 60 000 s. Light shift cancellation techniques were implemented to improve the mid and long term frequency stability. We presented also a compact demonstrator combining a novel custom-designed 895 nm VCSEL and a Cs-Ne microcell. A typical short-term frequency stability of 2.9×10^{-11} at 1 s is expected with correct adjustment of experimental parameters. Further studies are in progress to evaluate the mid and long term stability performances of the VCSEL-based clock.

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