Characterization of 894.6 nm VCSELs and application to a microcell-based atomic clock

R. Vicarini, J. Rutkowski, V. Maurice, E. Kroemer, S. Galliou, C. Gorecki, and R. Boudot
FEMTO-ST, CNRS/UBFC/ENSMM
Besançon, France
rodolphe.boudot@femto-st.fr

***Abstract*—We report the characterization of 894.6 nm vertical-cavity surface-emitting lasers (VCSELs). The laser RIN is -105 dB/Hz at 1 Hz offset frequency for a laser power of 50 µW. The laser spectral linewidth is measured to be about 31.8 MHz. Such a VCSEL is used in a Cs-Ne microcell-based atomic clock prototype based on coherent population trapping (CPT). A preliminary fractional frequency stability of 3.8 10^{-11} $\tau^{-1/2}$ up to 1000 s and lower than 3 10^{-11} at 60 000 s averaging time is reported. Further tests are in progress to improve the clock mid-term and long-term frequency stability.**

Keywords—VCSEL, miniature atomic clock, coherent population trapping, micro-fabricated cell.

I. INTRODUCTION

Over the last decade, the combination of coherent-population trapping (CPT) physics, micro-electro-mechanical systems (MEMS), and semiconductor lasers technologies has led to the development of miniature atomic clocks (MACs) demonstrating a fractional frequency stability lower than 10^{-11} at one-day integration time, a hundred times better than those of widely used quartz crystal oscillators for a similar volume (~15 cm^3) and low power consumption (~150 mW) [1-3]. These MACs are of great interest for a number of civil and industrial applications such as mobile telecommunications, power networks, satellite-based navigation systems, or sensing applications. To date, a CPT-based MAC proposed by Microsemi is even commercially-available [2]. However, many laboratories or industries pursue their efforts towards the development of alternative MAC products.

Laser sources used in MACs are vertical-cavity-surface emitting lasers (VCSELs). The short-term fractional frequency stability of CPT-based MACs is known to be significantly improved by using a laser tuned on the alkali D_1 line [4]. For Cs MACs, different 895 nm VCSELs were developed [5-6]. Nevertheless, to our knowledge, finding commercially-available VCSELs at this wavelength for Cs MACs has long been a significant issue.

In this study, we report the characterization of novel 894.6 nm VCSELs dedicated to be used in a Cs MAC. These measurements include output optical power versus dc current and temperature, spectral linewidth, relative intensity noise (RIN) or frequency noise [7]. For application, a VCSEL is used in a Cs microcell-based CPT atomic clock. A preliminary fractional frequency stability of 3.8 10^{-11} $\tau^{-1/2}$ up to about 1000 s is reported, achieving a value lower than 3 10^{-11} at 60 000 s.

II. VCSEL CHARACTERIZATION

VCSELs used here are resonant with Cs atom for a temperature-current couple is about 17°C-1.4 mA. Figure 1 reports the measured RIN of the VCSEL for a laser power of 50 µW.

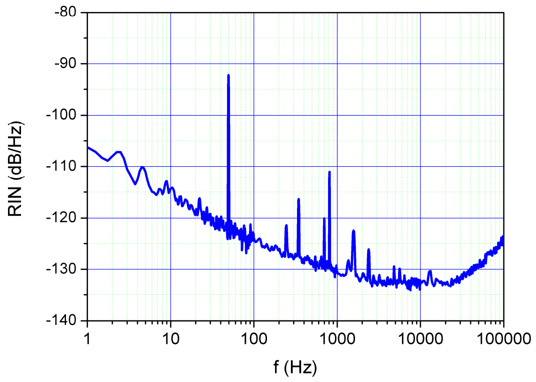

Fig. 1. RIN of the VCSEL. The VCSEL power is here 50 µW.

Figure 2 shows a measurement of the beat-note spectrum between the VCSEL and a DFB laser. The spectrum is fitted by a Lorentzian function. The VCSEL spectral linewidth is measured to be 31.6 MHz.

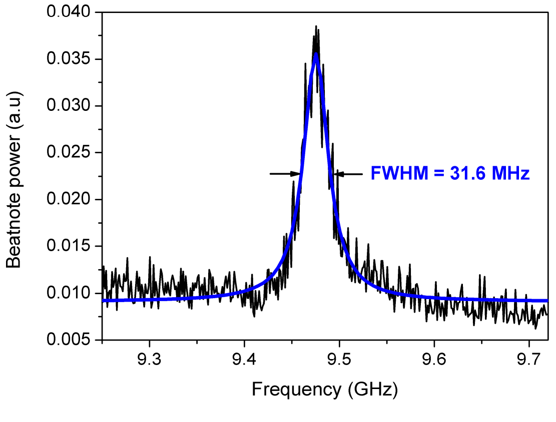

Fig. 2. Spectral linewidth of the VCSEL.

III. CLOCK SETUP AND RESULTS

Figure 3 shows the microcell-based CPT clock experimental setup. The cell is fabricated using the dispenser-based technology described in [8]. It is filled with Ne buffer gas, temperature-stabilized at about 79°C. A static magnetic field is applied in order to split the different Zeeman transitions. The ensemble is surrounded by a single-layer mu-metal magnetic shield. Atoms in the cell interact with a bi-chromatic optical field generated by direct microwave modulation at 4.6 GHz of the VCSEL injection current through a bias-tee. Atoms are pumped in a dark state when the frequency difference between both first-order optical lines equals the Cs ground-state hyperfine splitting (~9.192 631 GHz). The light power transmitted through the cell is detected by a photodiode. The photodiode output signal is used both for laser frequency stabilization and local oscillator frequency stabilization.

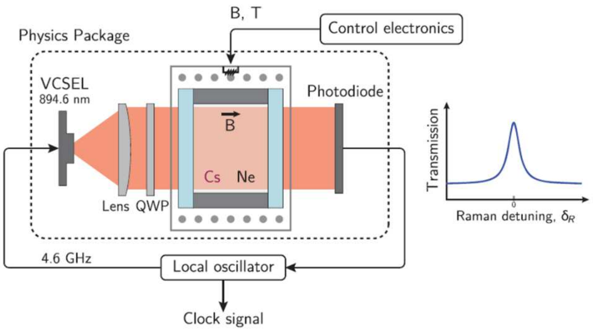

Fig. 3. Schematic of the Cs CPT clock. The laser frequency-stabilization is not shown here.

Figure 4 shows the Allan deviation of the Cs-Ne microcell-based CPT clock. It is measured to be $3.8\ 10^{-11}\ \tau^{-1/2}$ up to 1000 s and lower than $3\ 10^{-11}$ at 60 000 s averaging time. These performances are encouraging and demonstrate the potential of the tested VCSELs, associated with microcells, for the development of high-performance MACs.

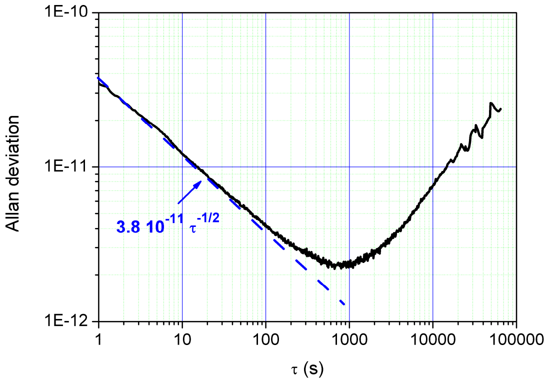

Fig. 4. Allan deviation of the CPT clock.

A noise budget will be reported at the conference to evaluate the main contributions to the clock fractional frequency stability. Some advanced light-shift cancellation or reduction techniques inspired from [3] or [9] will be tested to improve the clock mid-term frequency stability. Moreover, we think that the clock frequency stability for integration times higher than 1000 s could be improved thanks to the use of a further miniaturized MAC physics package with optimized thermal design. Latest results will be shown at the conference.

ACKNOWLEDGMENTS

The authors thank colleagues in FEMTO-ST (P. Abbé, C. Rocher, S. Bargiel, N. Passilly, M. Abdel Hafiz), Délégation Générale de l'Armement (DGA, Rapid HABAC project), Région de Franche-Comté and LabeX FIRST-TF.

REFERENCES

[1] S. Knappe, V. Shah, P. D. D. Schwindt, L. Hollberg, J. Kitching, L. A. Liew and J. Moreland, A microfabricated atomic clock, Aplpied Physics Letters 85, 9, 1460 (2004).

[2] https://www.microsemi.com/products/timing-synchronization-systems/embedded-timing-solutions/components/sa-45s-chip-scale-atomic-clock

[3] Y. Zhang, W. Yang, S. Zhang and J. Zhao, Rubidium chip-scale atomic clock with improved long-term stability through lihgt intensity optimization and compensation for laser frequency detuning, JOSAB 33, 8, 1756 (2016).

[4] M. Stähler, R. Wynands, S. Knappe, J. Kitching, L. Hollberg, A. Taichenachev and V. I. Yudin, Coherent population trapping resonances in thermal 85Rb vapor: D1 versus D2 line excitation, Optics Letters 27, 1472-1474 (2002).

[5] D. K. Serkland, K. M. Geib, G. M. Peake, R. Lutwak, A. Rashed, M. Varghese, G. Tepolt and M. Prouty, Vertical-cavity surface-emitting lasers, Proc. SPIE 6484 (2006).

[6] F. Gruet, A. Al-Samaneh, E. Kroemer, L. Bimboes, D. Miletic, C. Affolderbach, D. Wahl, R. Boudot, G. Mileti and R. Michalzik, Metrological characterization of custom-designed 894.6 nm VCSELs for miniature atomic clocks, Optics Express 21, 5781-5792 (2013).

[7] E. Kroemer, J. Rutkowski, V. Maurice, R. Vicarini, M. Abdel Hafiz, C. Gorecki and R. Boudot, Characterization of commercially-available vertical cavity surface emitting lasers tuned on Cs D1 line at 894.6 nm for miniature atomic clocks, Applied Optics 55, 31, 8839 (2016).

[8] M. Hasegawa, R. K. Chutani, C. Gorecki, R. Boudot, P. Dziuban, V. Giordano, S. Clatot and L. Mauri, Microfabrication of Cs vapor cells with buffer gas for MEMS atomic clocks, Sensors Actuators A 167, 594 (2011).

[9] V. Shah, V. Gerginov, P. D. D. Schwindt, S. Knappe, L. Hollberg and J. Kitching, Continuous light-shift correction in modulated coherent population trapping clocks, Applied Physics Letters 89, 151124 (2006).