Cs microcell microwave and optical frequency references at FEMTO-ST

C. Carlé[1], A. Gusching[1], N. Passilly[1], I. Ryger[1], J. Millo[1], M. Petersen[1], D. Brazhnikov[2,3], M. Abdel Hafiz[1] and R. Boudot[1]

1 *FEMTO-ST, CNRS, UBFC, ENSMM, 26 rue de l'épitaphe 25030 Besançon cedex*
2 *Novosibirsk State University, 1 Pirogov Street, Novosibirsk 630090, Russia*
3 *Institute of Laser Physics SB RAS, 15B Lavrentiev Avenue, Novosibirsk 630090, Russia*
Email : rodolphe.boudot@femto-st.fr

FEMTO-ST laboratory has worked over the last 15 years on the development of miniaturized microwave Cs cell atomic clocks. These clocks are based on coherent population trapping (CPT) [1] and rely on the interaction of thermal cesium atoms confined in a microfabricated vapor cell with an optically-carried 9.192 GHz microwave signal generated by direct modulation of a vertical-cavity surface-emitting laser (VCSEL). At CPT resonance, the atoms are trapped in a so-called dark state. This yields to the detection of a narrow CPT resonance that can be used for the stabilization of the frequency of a local oscillator onto the microwave atomic transition frequency.

The Cs vapor microcell, shown in Figure 1(a), consists of two cavities, connected by thin channels and etched into a silicon substrate, sandwiched between two anodically-bonded glass substrates [2]. The main originality of this technology is that the alkali filling is performed after final sealing of the cell by local laser activation of a pill dispenser embedded priorly into the cell during the fabrication process. The MEMS cell is then inserted into an ultra-compact physics package, in which the cell is associated with the VCSEL and several optical components for the routing, polarization and detection of the laser beam (fig. 1(b)). This physics package can be ultimately embedded onto an electronics card (figure 1c) or used onto a table-top clock prototype to perform CPT spectroscopy and clock frequency metrology experiments.

Over the last years, significant valorization efforts in collaboration with Tronics Microsystems and Syrlinks have conducted to the development of industrial miniaturized atomic clock prototypes in France [3,4]. These clocks target a total volume of about 15 cm^3, a power consumption of 150 mW and an Allan deviation of about 10^{-11} at 1 day integration time in order to be used in numerous applications including network synchronization, GNSS-denied navigation systems or secure communications. For illustration, Figure 1(d) shows the Allan deviation of a microcell atomic clock developed at the laboratory, in comparison with performances of a traditional quartz-crystal oscillator. The fractional frequency stability of the clock is 8 10^{-11} at 1 s and 6 10^{-12} at 1 day integration time. We'll also present in this conference some recent studies that explore the use of Ramsey-CPT spectroscopy for the development of miniature CPT-based atomic clocks [5].

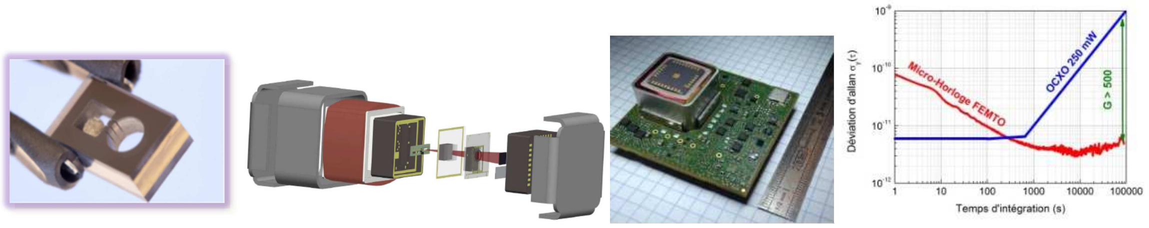

Figure 1. From left to right: (a) Photograph of a Cs vapor microfabricated cell. (b) Ultra-compact physics package that combines a VCSEL, optics, a MEMS cell, a photodiode and heating and magnetic elements. Extracted from [3]. (c) Photograph of a clock prototype with physics package and electronics (Tronics, Syrlinks, FEMTO-ST). (d) Allan deviation of a clock prototype at FEMTO-ST.

Despite remarkable performances, CPT-based microwave miniature atomic clocks present some intrinsic limitations: the clock transition frequency is in the microwave domain at “only” 10 GHz, the FM noise of the VCSEL contributes strongly to the clock short-term stability while the presence of buffer or spurious gas in the cell can contribute to the cell inner atmosphere evolution and jeopardize the clock mid-long term stability.

From this, we have undertaken at FEMTO-ST the development of microcell-based optical frequency references. These references will target the demonstration of 100 times better stability than CPT-based microwave chip-scale atomic clocks while presenting a competitive size-power budget. In this domain, NIST has recently demonstrated convincing results with the demonstration of the photonic integration of a microcell optical clock using the 778 nm two-photon transition of Rb atom. This clock demonstrates a fractional frequency stability of 4 10^{-12} $\tau^{-1/2}$ until 1000 s [6] (with τ the integration time), later improved at 2.9 10^{-12} $\tau^{-1/2}$ through an extremely compact optical breadboard [7].

At FEMTO-ST, we have started the development of a Cs microcell optical frequency reference based on dual-frequency sub-Doppler spectroscopy [8,9]. This approach consists to make Cs atoms interact with two orthogonally-polarized counter-propagating dual-frequency optical fields in a MEMS cell. This approach implies the contribution of Zeeman and hyperfine dark states, optical pumping effects [9] and allows the detection of high-contrast sign-reversed enhanced-absorption sub-Doppler resonances.

Two stabilized lasers (one DFB and one ECDL) were implemented on a table-top experiment using this technique. Each setup is composed of a diode laser, a Mach-Zehnder electro-optic modulator (EOM) to produce the dual-frequency optical field and an acousto-optic modulator for power stabilization of the laser beam.

The preliminary short-term stability of the laser beat-note is 1.5 10^{-12} $\tau^{-1/2}$ until 100 s and is currently limited by the intermodulation effect linked to the intrinsic frequency noise of the DFB laser. These short-term performances are encouraging and clearly better than those of microwave commercial chip-scale clocks. The contribution of numerous frequency shifts onto the clock mid-term frequency stability is under progress and will be discussed at the conference, as well as latest improvements of the experiment, in terms of cell technology or stability characterization.

References:

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