Advances in the development of an eXtra Small Atomic Reference (XSAR)

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Abstract – **This paper describes a one year work started at CSEM in 2009. At the end of the project, a system level prototype of an eXtra Small Atomic Reference (XSAR) should be realized by teaming up different know-hows available at CSEM. The work followed a top down systematic. A breadboard level coherent population trapping (CPT) atomic clock working on Rubidium-87 atoms confined in a glass cell and controlled by laboratory electronics was built at first. The different building blocks of this breadboard CPT atomic clock were characterized in order to select them for the XSAR prototype. The CPT signal and the corresponding operating parameters were accordingly optimized. The knowledge acquired in the first phase was used to define the goals to be reached with the first XSAR prototype. Priorities were settled on the miniaturization of the optical assembly unit (laser and optics), the atomic vapor cell unit and finally the RF electronic unit. After one year, the first XSAR prototype showed promising short term frequency stability reaching $1.8{\bullet}10^{-11}\ \tau^{-1/2}$ when fully driven by laboratory RF electronics and $2{\bullet}10^{-10}\ \tau^{-1/2}$ when driven by an integrated RF synthesizer.**

1. INTRODUCTION

CSEM is a privately held research and development company. Its main fields of activity are micro- and nanotechnologies, microelectronics, systems engineering, microrobotics, photonics, information and communication technologies. With its expertise in atomic clocks, micro-optics, MEMS fabrication techniques, low-power integrated electronics, miniaturization and micro-packaging, CSEM has everything in house for the development at the full system level of a miniature atomic cell-based clock based on coherent population trapping (CPT).

Today commercial cell-based atomic clocks have a microwave cavity surrounding the atomic cell (double resonance scheme) and use a traditional discharge lamp as the light source interrogating the atoms. The dimensions of these devices are limited by the wavelength of the resonant microwave frequency that limits the microwave cavity size, a limitation which is avoided by using the CPT principle [1] [2] [3] [4] where the microwave frequency is directly coupled to a VCSEL via its injection current. Lower power consumption, compactness, clean optical spectrum and high-modulation bandwidth are major advantages of the VCSEL over the discharge lamp. Commercial cell-based atomic clocks are also limited in their size reduction because of the use of standard glass blowing cells which sizes can reach several millimeters but not less. MEMS cell containing the atomic vapor along with buffer gases can be fabricated down to sub-millimeter sizes [5] [6], a technology allowing for a further important atomic clock miniaturization. The complicated electronics needed to control such a miniature cell-based atomic clock impacts on its size and its power consumption. Integrated, low noise and low power solutions mastered by CSEM should open new atomic clock miniaturization and low-power performances.

The future applications of atomic clocks with sub-cubic centimeter volume and battery-compatible power consumption will find applications in the fields of telecommunications (network synchronization), navigation (GPS/Galileo receivers) and on-board satellite atomic clocks. The availability of high-performance miniature time-keeping devices with low power consumption will open the way to many new applications too.

2. BREADBOARD LEVEL CPT ATOMIC CLOCK

The first phase of the XSAR project consisted in building a working breadboard atomic clock (Fig. 1) made off all the representative building blocks thought to be used for the final prototype. We settled on an atomic clock working with a vertical cavity surface emitting laser (VCSEL) whose frequency matches the favored D1 transition [7] of Rubidium-87 (^{87}Rb) atoms, i.e. 795 nm. The coherent population trapping (CPT) technique is realized by measuring the reduction of the optical absorption of ^{87}Rb. This reduction is observed when, by a direct modulation of a single VCSEL, the frequency difference of the two generated laser beams equals the frequency difference of the ground state hyperfine split of the alkali atoms.

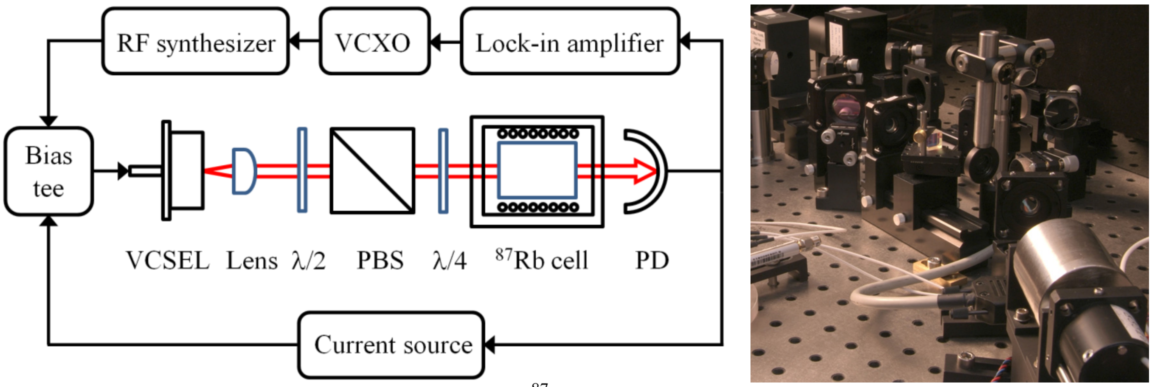

Fig. 1. Left: Schematic illustration of the breadboard ^{87}Rb CPT atomic clock. Right: Picture of the physics package breadboard.

The TO46-packaged VCSEL is hold in a laser head where its temperature is regulated by means of a Peltier element coupled to a negative temperature coefficient (NTC) thermistor. The laser injection current is delivered by a self-made low-noise laboratory current source which is used to lock the laser frequency to the selected absorption band. A voltage-controlled crystal oscillator (VCXO) referenced synthesizer delivers the 3.4 GHz laser modulation. Both the injection current and RF modulation are directly coupled into the laser by means of an external bias tee. The resulting emitted bichromatic laser beam is collimated by a short focal length lens. The collimated linearly polarized laser beam is attenuated by an attenuator made of a half-wave plate and a polarizing beamsplitter. The remaining transmitted light beam is first circularly polarized with a quarter-wave plate and passes then through a 25 mm diameter and 10 mm long buffered atomic vapor cell. The cell is hold in a double layer magnetic shielding, is temperature regulated, and is surrounded by a solenoid. The absorption spectrum and more specifically the reduction of optical absorption due to the CPT phenomenon is measured after the cell by means of a silicon photodetector. The CPT signal is fed to a laboratory DSP lock-in amplifier which controls and corrects the 10 MHz output frequency of the VCXO.

The breadboard ^{87}Rb CPT atomic clock was used to approve the choice of the VCSEL. The selected laser source showed to meet the requirements in terms of emitted wavelength and its tuning range, linear polarization and its stability, consumption, linewidth, modulation bandwidth, frequency noise, relative intensity noise (RIN) and side-mode suppression ratio (SMSR). The selected ^{87}Rb vapor glass cell with buffer gas (Ne) showed 0-0 CPT signal of the order of 220 Hz linewidth and 4% contrast. By optimizing the operating parameters (optical power, cell temperature, modulation index, lock-in sensitivity and time constant), short term frequency stability of the order of $2 \cdot 10^{-11}\ \tau^{-1/2}$ could be measured. These first results allowed starting with the miniaturization process in which three main units were considered: 1. the optical assembly unit (VCSEL + optics), 2. the atomic vapor cell unit, 3. the RF electronic unit (RF synthesizer + lock-in amplifier).

3. MINIATURIZATION OF THE OPTICAL ASSEMBLY UNIT

It was decided to mount the XSAR prototype on a standard RF printed circuit board in a stacking way, the VCSEL being at the bottom of the stack and the photodetector at the top of it. Bare VCSEL chips having a size of 450 x 450 µm were ordered. In order to heat and maintain them at the operating temperature of around 75°C, a dedicated heater chip with heater and temperature sensor lines was developed. Its dimensions are 1.1 x 0.9 mm footprint for 500 µm thickness (Fig. 2). The heating and sensor meanders were designed to compensate for induced magnetic fields. The temperature sensor line was designed for maximizing its resistance. At room temperature, the sensor line was measured to have a resistance of around 1400 Ω. The VCSEL chip is directly mounted on top of the heater chip and both of them are then wire-bonded to the PCB as illustrated in Fig. 2.

The heater chip is controlled by a dedicated laboratory electronic for temperature regulation whereas the VCSEL chip is controlled by our low-noise self-made laboratory current source. The VCSEL unit mounted on the PCB showed similar optical properties than the commercial TO46 VCSEL used in the breadboard level described above. Its wavelength could be tuned to Rubidium D1 absorption lines and its side-mode suppression ratio showed to meet the requirements at the nominal operation temperature.

The optical assembly has been miniaturized to the millimeter scale too and is mounted above the VCSEL unit.

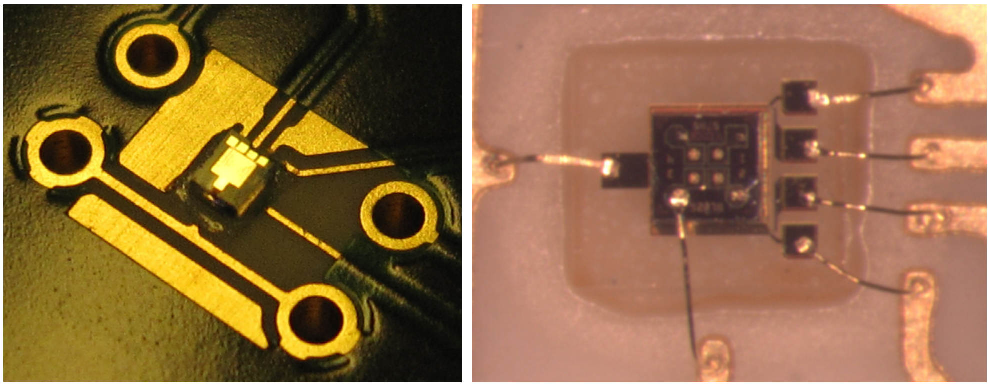

Fig. 2. Left: 1.1 x 0.9 x 0.5 heater chip mounted on a PCB. Right: VCSEL chip mounted on top of the heater chip.

4. MINIATURIZATION OF THE ATOMIC VAPOR CELL UNIT

Miniaturization of the ^{87}Rb vapor cell has been split in two separate phases. The first phase consisted in procuring the smallest reproducible glass cells and the second phase consisted in developing a cell micro-fabrication process using the techniques associated to micro-electromechanical systems (MEMS).

Glass blown cells with dimensions of the order of 5 mm diameter and 6 mm total length were successfully fabricated and filled with ^{87}Rb vapor along with 30 mbar of a mixture [8] of nitrogen (N_2) and argon (Ar) buffer gas (Fig. 3). Typical 0-0 CPT signals measured with these cells on the breadboard setup showed linewidth around 550 Hz with a contrast of about 2%.

The development of the micro-fabrication process was made at CSEM. The cell's global structure is a typical sandwich of glass-silicon-glass wafers bonded by anodic bonding. Different filling techniques were explored with very promising results. We could fabricate 10 x 10 x 2 mm tight MEMS cells with Rubidium inside but the control of the buffer gas pressure is still to be mastered. Another cell jointly fabricated by the EPFL and the University of Neuchâtel in Switzerland using different bonding and filling processes was tried. This cell showed very promising results as measured by the CPT signal of about 2.7 kHz linewidth.

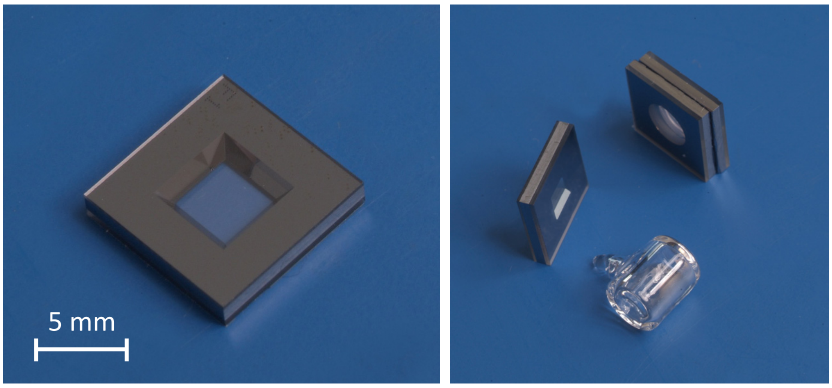

Fig. 3. Left: 10 x 10 x 2 mm MEMS cell fabricated at CSEM. Right: MEMS cells (origins: left: CSEM; right: EPFL-University of Neuchâtel) and 5 mm diameter 6 mm long glass cell (bottom).

Implementing a miniature MEMS cell in our prototype was actually not possible. We settled therefore on the implementation of a miniature glass blown cell illustrated in Fig. 3. The dimensions of the final XSAR prototype will consequently not be representative of the miniaturization realized for the optical assembly. Fig. 4 illustrates the glass cell in its dedicated single layer 19 mm diameter magnetic shielding with heaters, thermistor and solenoid.

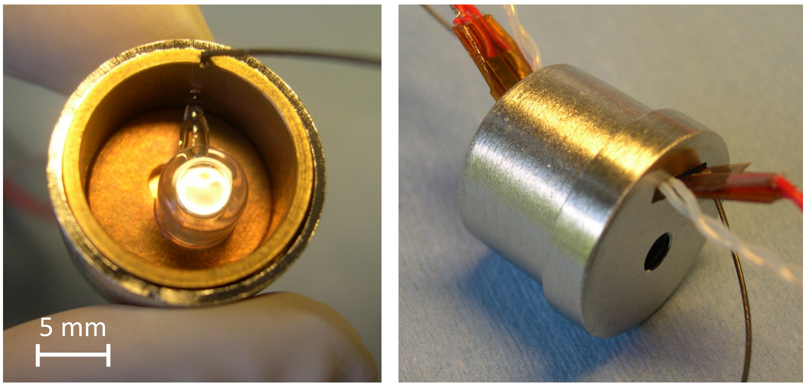

Fig. 4. Miniature glass cell in its 19 mm diameter magnetic shielding (heater, thermistor and solenoid included).

5. MINIATURIZATION OF THE RF ELECTRONIC UNIT

Fig. 5 illustrates the miniaturization process made for the RF electronic unit. The entire laboratory RF unit has been integrated in a 2 mm square IC developed at CSEM. The chip replaced the instrument scale RF synthesizer and was implemented in the XSAR prototype. First frequency stability measurements were very promising and further developments are currently on-going.

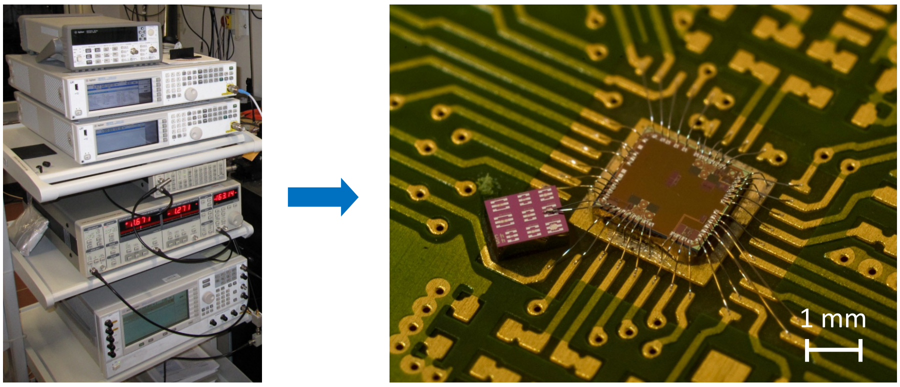

Fig. 5. Left: Laboratory RF electronic unit (VCXO, RF synthesizer and lock-in amplifier). Right: Integrated RF synthesizer unit (LO, RF synthesizer and lock-in amplifier).

6. FIRST XSAR PROTOTYPE

The miniaturization processes described in this paper allowed to build a first XSAR prototype (Fig. 6). The physics package of the prototype is mounted on a 50 x 60 mm PCB with standard SMA and SMB connectors. The ^{87}Rb vapor cell unit represents most of the size. A photodetector on top of the cell unit is missing in Fig. 6.

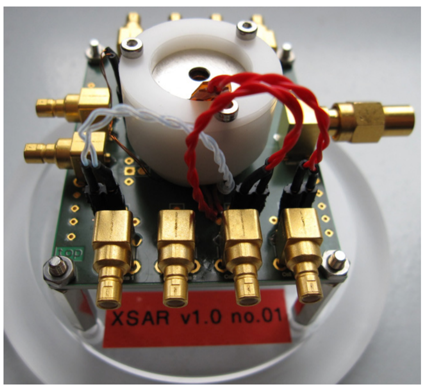

Fig. 6. Physics package of the first XSAR prototype (photodetector is missing). PCB dimensions are 50 x 60 mm.

Driving this first XSAR prototype with laboratory electronic allowed us to measure frequency stability reaching $1.8 \cdot 10^{-11}$ @ 1s and $1.6 \cdot 10^{-12}$ @ 256s as illustrated in Fig. 7. The long term frequency stability is in line with our expectations and has not been yet tackled. Driving the same prototype with the integrated RF electronic unit showed very promising results with preliminary short term frequency stability reaching $2 \cdot 10^{-10}\ \tau^{-1/2}$.

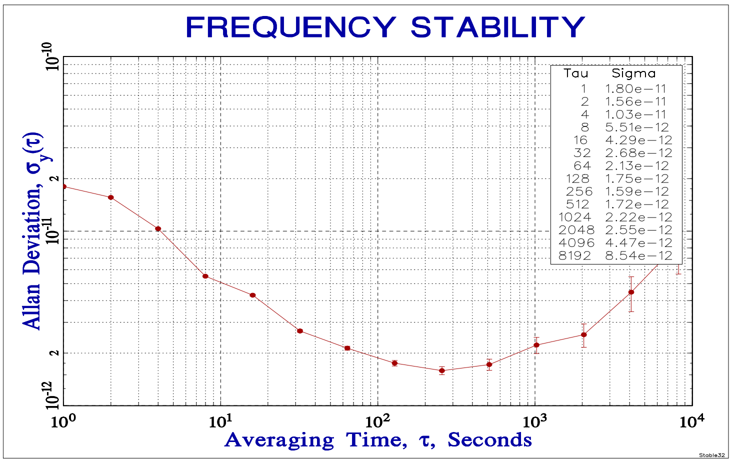

Fig. 7. Frequency stability measured with laboratory electronics on the first XSAR prototype.

CSEM has started a second phase for its XSAR project with specific priorities. One of the main priorities was settled on the fabrication of miniature MEMS cells with reproducible content and additional functionalities. Work will also be done on the packaging of the clock in order to improve the thermal management and the global power consumption. Further work will also be conducted in order to fully characterize the integrated RF electronic unit and to integrate additional functionalities. CSEM plans to be able to build the second generation of XSAR by the end of 2010.

CONCLUSION

The results of the first CSEM XSAR prototype have been presented. A breadboard clock test bench has been developed and is working. A frequency stability of $1.8 \cdot 10^{-11}\ \tau^{-1/2}$ has been measured that fully validates the test bench. The different clock building blocks could hence be individually tested. A first clock prototype has been assembled and is under test as well as an integrated RF electronics. The preliminary results are very promising with a measured frequency stability of $2 \cdot 10^{-10}\ \tau^{-1/2}$. The next steps are to fully characterize the RF electronic unit, update the physics package towards more integration and possibly better thermal management, and integrate a MEMS-type atomic vapor cell. The project is ongoing and we expect to report new results soon.

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