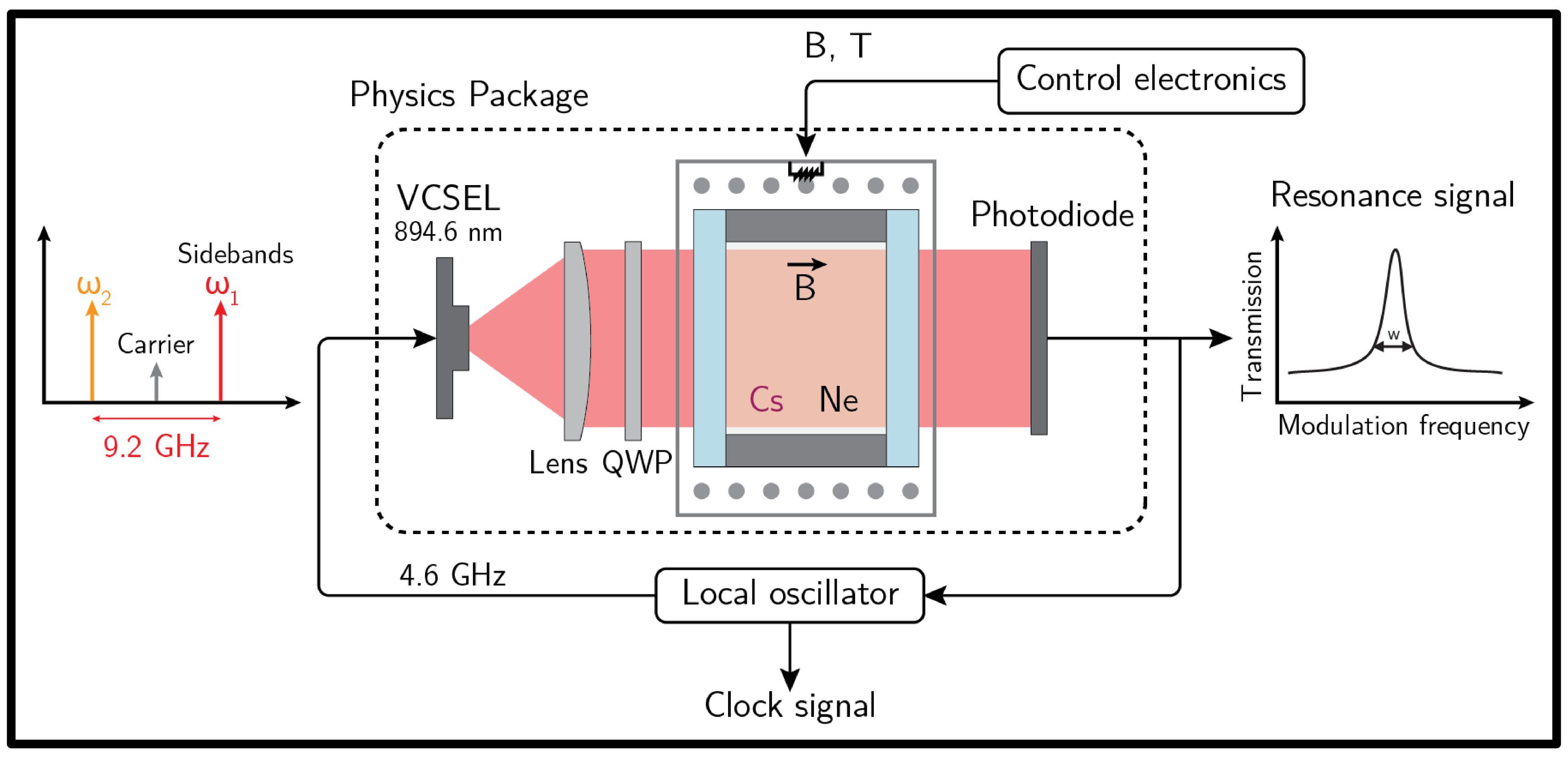
Miniaturized atomic clock with pulsed interrogation and advanced MEMS cell technology

C. Carlé, M. Abdel Hafiz, S. Keshavarzi, R. Vicarini, V. Maurice, N. Passilly, and R. Boudot

femto-st SCIENCES & TECHNOLOGIES — RÉPUBLIQUE FRANÇAISE Liberté Égalité Fraternité — cnes CENTRE NATIONAL D'ÉTUDES SPATIALES

Miniaturized atomic clocks (MACs) [1] exhibit **unrivaled size-power-stability budget** and replace OCXOs in a growing number of applications.
However, their long-term stability is still limited by two main contributions: **light-shits** and instability of the **cell inner atmosphere**.
To tackle these effects, we develop a clock that combine **Ramsey-based interrogation** [2,3] protocol and **advanced MEMS cell technology [4].**

MACs: Basics, objectives and applications



Cs atoms in a MEMS cell interact with an optically-carried 9.192 GHz signal.
Atoms are pumped in a quantum dark state (coherent population trapping [5]).

Typical objectives :
Volume: $15\ cm^3$
Power consumption: $100-150\ mW$
External temperature: -40 to $+80°C$
Stability: 10^{-11} at 1 day ($1\ \mu s/day$)

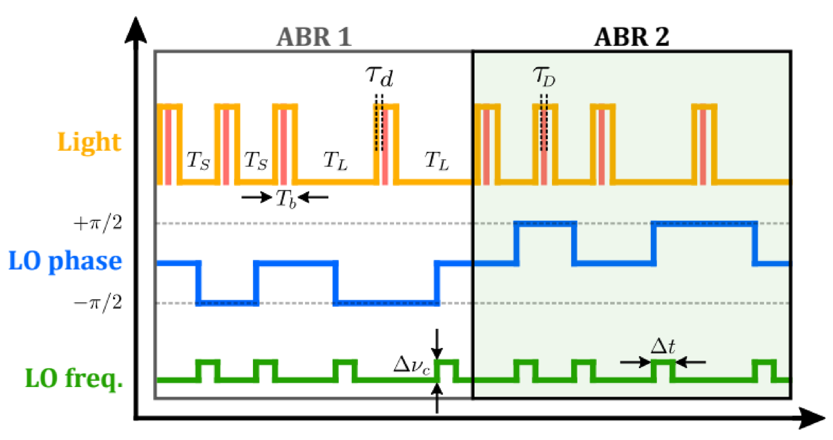
100 times better stability than OCXOs with the same size-power budget.

Underwater sensors	Defense systems	Avionics, Transports, Smart grids, secure communications
(Seismic research, gas/oil exploration)	*(Radios, GPS-denied receivers, unmanned aerial vehicles)*	

Symmetric Auto-Balanced Ramsey (SABR)

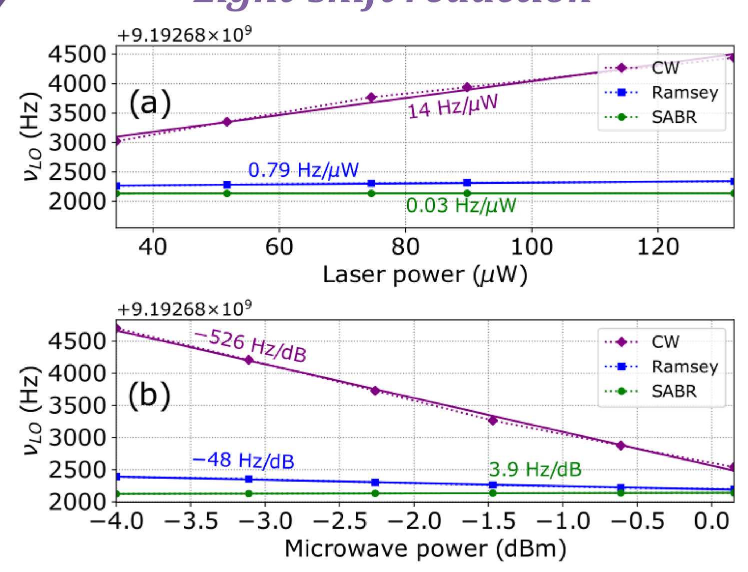
Atoms interact with a sequence of optical CPT pulses separated by a free-evolution dark time *T* [6].

SABR sequence



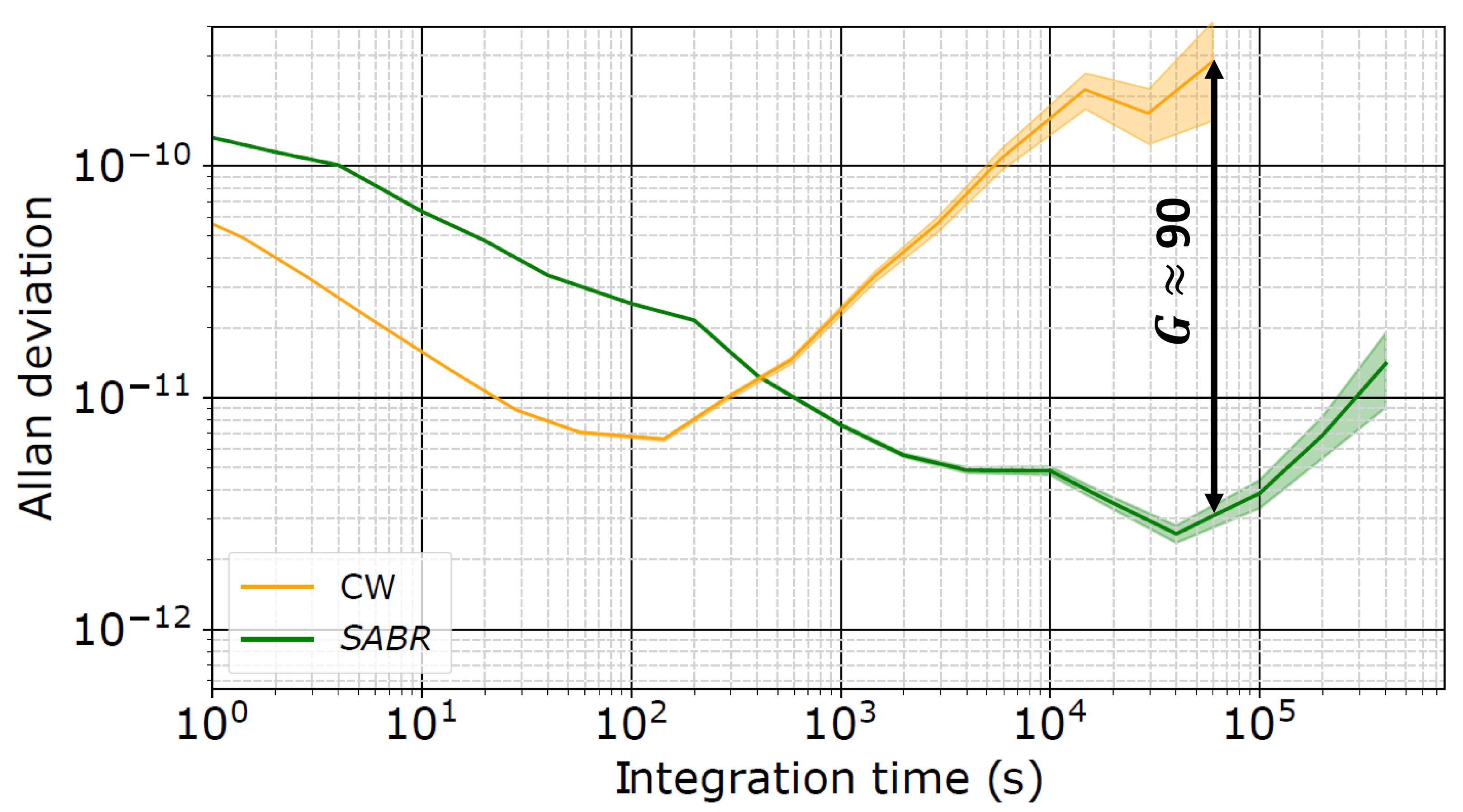
Sequence composed of *two symmetrical sub-sequences* (ABR1 [7] and ABR2) to minimize an atomic memory effect [3].

Light-shift reduction



The dependence of the clock frequency to light-field parameters is reduced by a factor higher than 100 (vs CW case).

Clock frequency stability

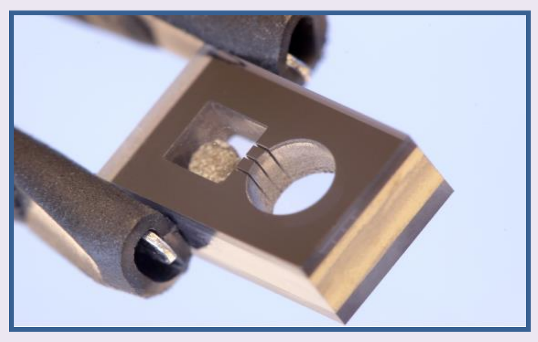


Improvement of the clock Allan deviation by a *factor 90 at $6*10^4\ s$* (vs CW case).

Light-shift mitigation
⇒ Improvement of the clock Allan deviation for $\tau > 100\ s$ [8]

Advanced MEMS cell technology

Cs vapor microfabricated cell [9]

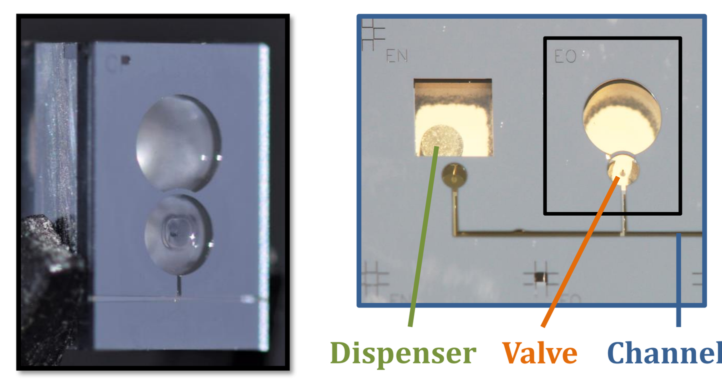


- glass-silicon-glass structure
- External dimensions: $6*4*2.5$ mm
- 1 pill cavity + 1 CPT cavity
- Ne buffer gas pressure (70-100 Torr)
- Alkali source = pill dispenser
- (laser activation after final sealing)

Drawbacks: limited temperature range (no N_2) + impurities

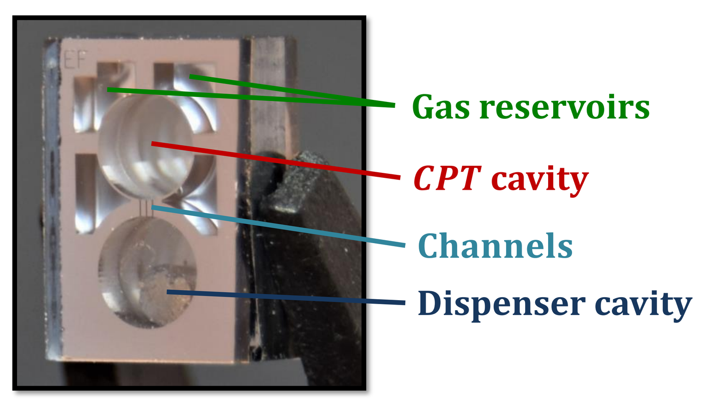
Novel MEMS cell filling approach [10]

Make seal membranes



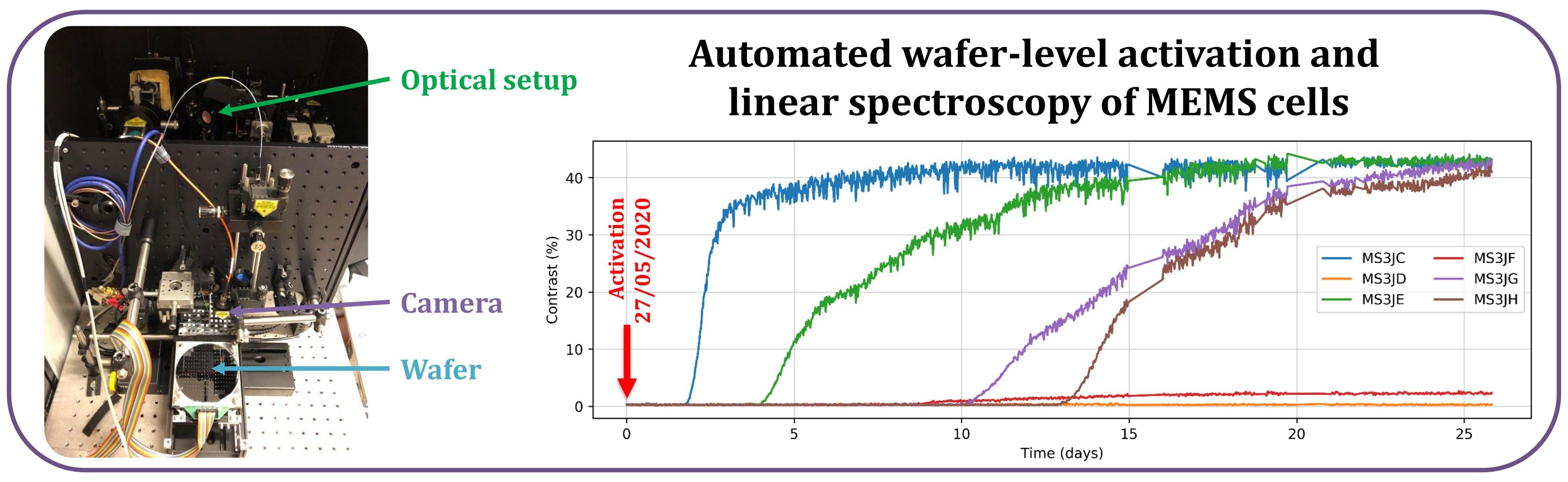
One single pill to fill many cavities, locally sealed *by laser-deflected glass membranes*

Gas reservoirs

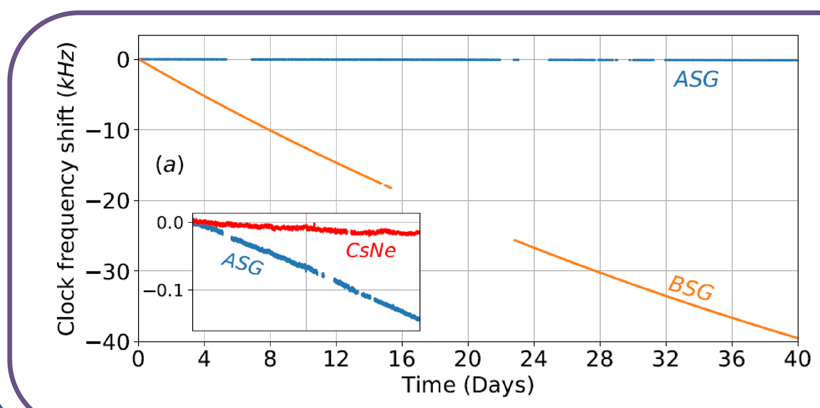


Use of buffer gas mixtures (N_2-Ar) without being perturbated by the dispenser.

Automated wafer-level activation and linear spectroscopy of MEMS cells



Low permeation glass substrates



- **B**oro**S**ilicate **G**lass (*BSG*)
- **A**lumino**S**ilicate **G**lass (*ASG*)

$$P(t) = P_{ext} - (P_{ext} - P_{in})e^{-\frac{t}{\tau}}$$

Gas permeation is strongly reduced with ASG

The **Symmetric Auto-Balanced Ramsey (SABR)** reduces light-shifts by more a factor higher than 100.
Proof of concept of an **advanced MEMS cell technology** using laser-actuated hermetic seal membranes [8] and low permeation glass substrates.
A clock Allan deviation of $3.8*10^{-12}$ at $10^5\ s$ was demonstrated.

References :

[1]: J. Kitching, Appl. Phys. Rev. 5, 031302 (2018).
[2]: N. F. Ramsey, Phys. Rev., vol. 78, 6, 695 (1950).
[3]: M. Abdel Hafiz *et al.*, Appl. Phys. Lett. 112, 244102 (2018).
[4]: V. Maurice *et al.*, US Patent 20180210403A1 (2018).
[5]: J. Vanier, Appl. Phys. B 81, 4, 421 (2005).
[6]: [2]: C. Carlé et al , IEEE UFFC 68, 3249 3256 (2021).
[7]: C. Sanner *et al.*, Phys. Rev. Lett. 120, 053602 (2018).
[8]: M. Abdel Hafiz *et al*, App. Phys. Lett., 120, 064101 (2021).
[9]: R. Vicarini, et al.. Sensors and Actuators, 280, 99 – 106 (2018).
[10]: V. Maurice et al., arXiv:2205.10440 (2022).

Contact

Clément Carlé
clement.carle@femto-st.fr

INSTITUT FEMTO-ST
15 B AVENUE DES MONTBOUCONS
25030 BESANÇON CEDEX - www.femto-st.fr

AGENCE INNOVATION DÉFENSE — cnrs — UNIVERSITé FRANCHE-COMTé — ensmm — utbm — membres de UBFC — FIRST TF — DGA — RÉGION BOURGOGNE FRANCHE COMTÉ — ANR — Oscillator IMP — Syrlinks — ASTRID