uLtra-stablE near-UV Cs mIcrocell-stabilized LAser (LEILA)

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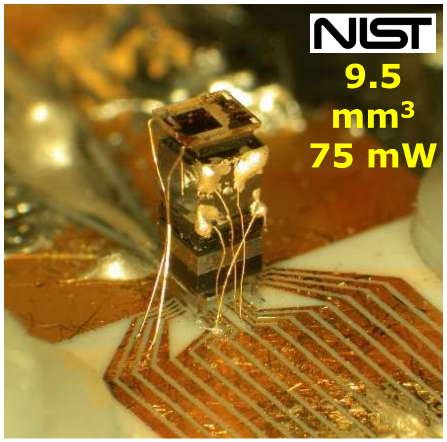
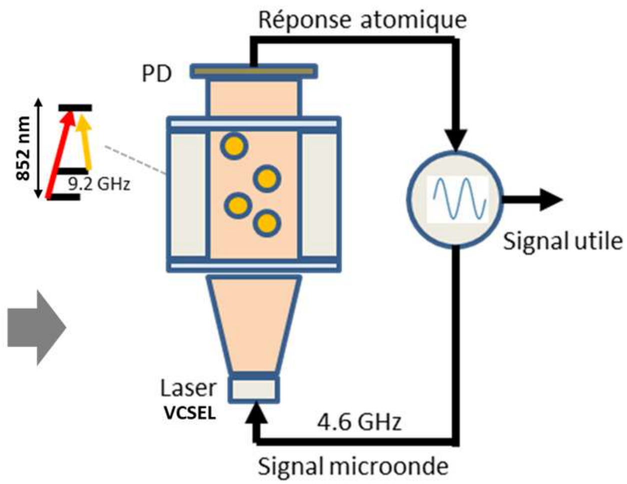
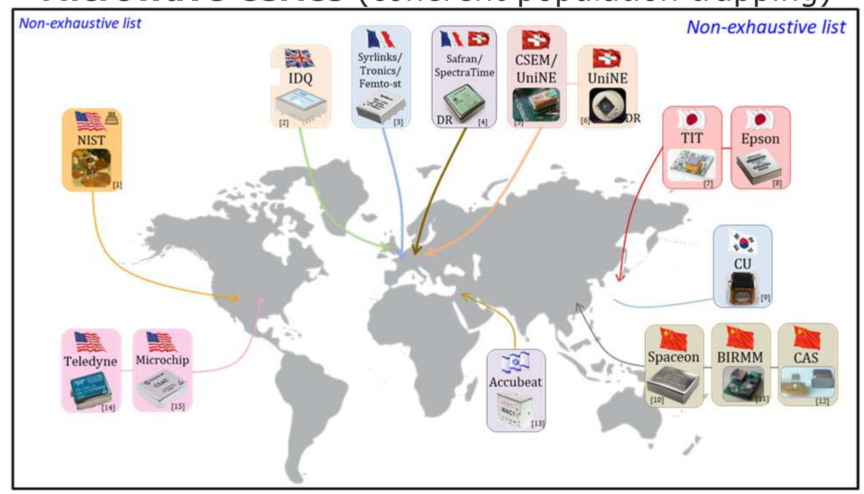
Context: Chip-Scale Atomic Clocks



S. Knappe et al., Appl. Phys. Lett. 85, 9 (2004)



Microwave CSACs (coherent population trapping)



Main stability limitations:
Short-term : laser (VCSEL) frequency noise
Long-term : buffer-gas induced collisional shifts

Volume < 20 cm³
Embedded devices

Consumption < 150 mW
Longer battery-powered missions

Operating temperature - 40 à 85°C
Compliant with industrial standards

Frequency stability 10^{-11} at 1 h and 1 day
Timing error < 1 µs/day

J. Kitching et al., Appl. Phys. Rev. 5, 031202 (2018)

Towards next-generation microcell optical clocks

Probe ultra-narrow transitions
Improve the cell purity

Increase the frequency ν_0
Probe optical transitions
(ν_0 > 300 THz)

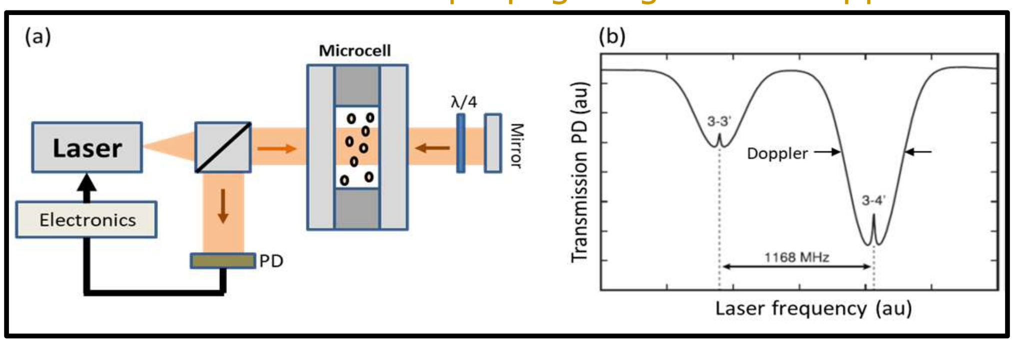
$$\sigma_y(\tau) = \frac{\Delta\nu}{\nu_0}\frac{1}{S/N}\tau^{-1/2}$$

Short-term stability of an atomic clock

Increase the SNR
Low-noise lasers
Detect high-signals

Sub-Doppler spectroscopy techniques

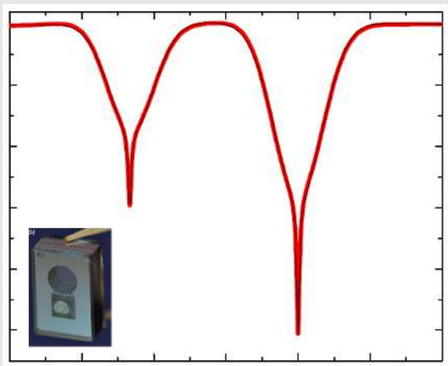
Hot vapor interacts with two counter-propagating fields: Doppler-free resonances



Simple architecture: 1 laser + 1 vapor cell / No laser cooling, no UHV

(Non-exhaustive) State-of-the-art of microcell optical references

Dual-frequency sub-Doppler spectroscopy (Cs 895 nm)



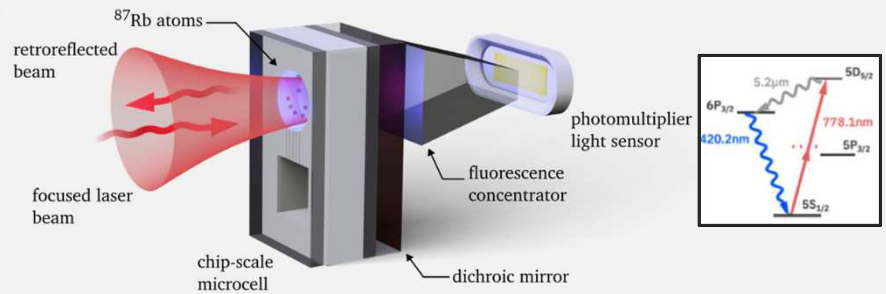
$3\text{x}10^{-13}\ \tau^{-1/2}$ up to 100 s

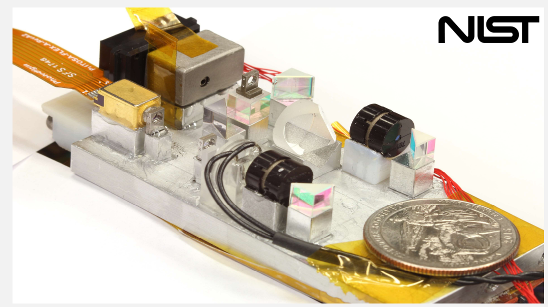
A. Gusching et al., Opt. Lett. 48, 6, 1526 (2023)

Requires a microwave-modulated optical field (EOM)

Complex architecture

Two-photon transition in Rb atom (778 nm)





$1.8\text{x}10^{-13}\ \tau^{-1/2}$ up to 100 s

Z. Newman et al., Opt. Lett. 46, 18 (2021)

$3\text{x}10^{-13}\ \tau^{-1/2}$ up to 100 s

M. Callejo et al., 2407:00841 ArXiv (2024)

Limitations:

Photon shot noise (blue photon collection)

Laser FM noise (intermodulation effect)

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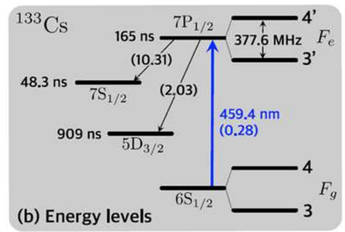
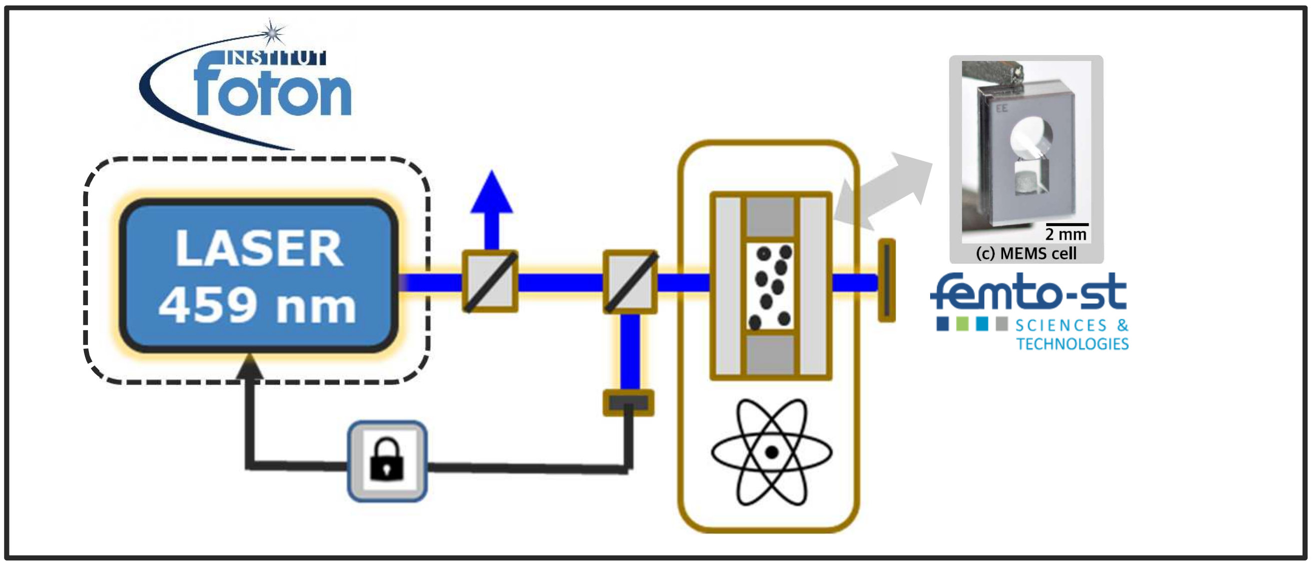
LEILA motivations: near a near-UV microcell optical reference

What about directly probing a blue transition ?

Cs $6S_{1/2}$ – $7P_{1/2}$ transition (459 nm)



*Transition frequency x 2
*Narrow natural linewidth ~ 1 MHz
*Simple scheme (saturated absorption)
*Progress of near-UV/blue lasers/optics

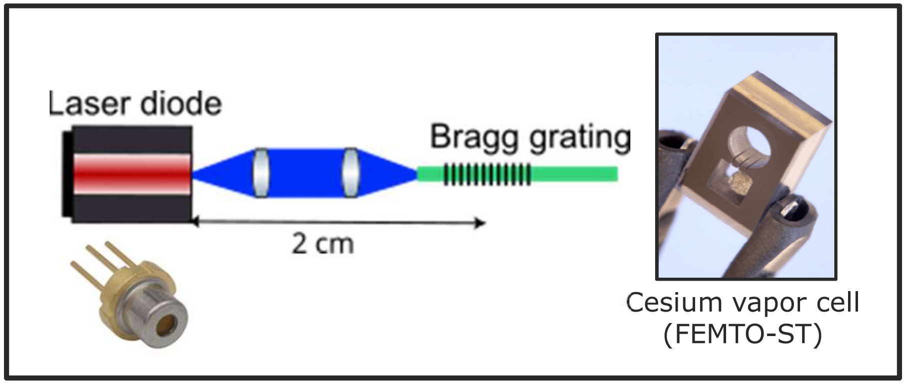


Axis 1: Blue laser (FOTON)

Axis 2: Microcell & Metrology (FEMTO)

Axis 3: Axis 1 + Axis 2
(FOTON + FEMTO)

Axis 1: 459 nm FGL for microcell reference - specifications



Specifications for the blue laser:

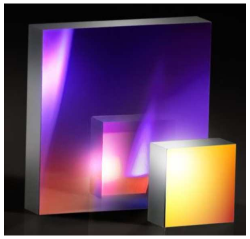
- Laser wavelength tunability to reach the atomic transition
- Laser wavelength modulation to implement PDH locking
- Low frequency noise (intermodulation effect)

$$\sigma(1s) = \frac{\sqrt{S_{\Delta\nu}(2fm)}}{2\nu_0}$$ ➡ σ(1s) = 10^{-13} ➡ $S_{\Delta\nu}(2fm) < 2 \times 10^4\ Hz^2/Hz$

C. Audoin et al. IEEE TIM 1991

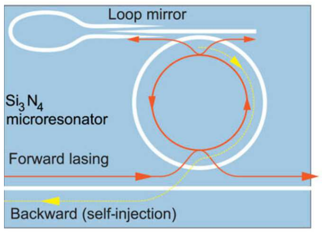
Axis 1: Narrow linewidth lasers in the 370-500 nm range

Diffraction grating



X. Zeng *et al* OL **39**, pp1685 (2014)

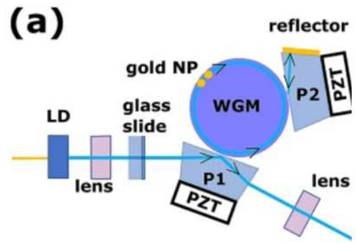
Integrated resonators



A. Siddharth *et al.* APL Photonics **7** L046108 (2022)

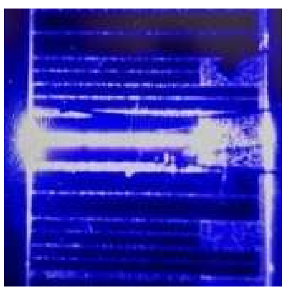
M. Corato-Zanarella *et al.* Nat. Photonics **17** 157-164 (2023)

Whispering gallery mode (WGM) resonator

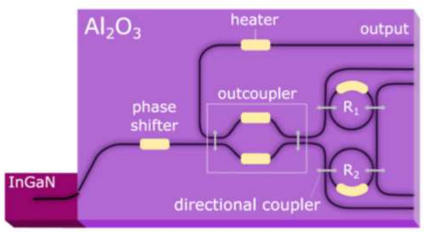


A.A. Savchenkov, *et al. Sci Rep* **10**, pp 16494 (2020)

Distributed feedback laser

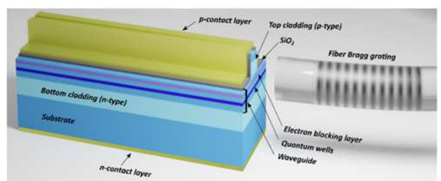


E. Trageser et al. OE **32**, pp 23372 (2024)

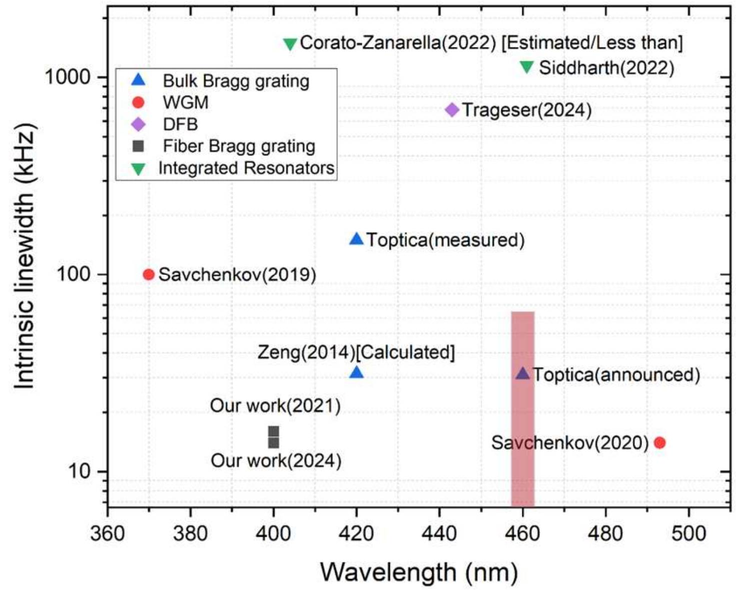


C. Franken et al. Arxiv 2302.11492 (2023)

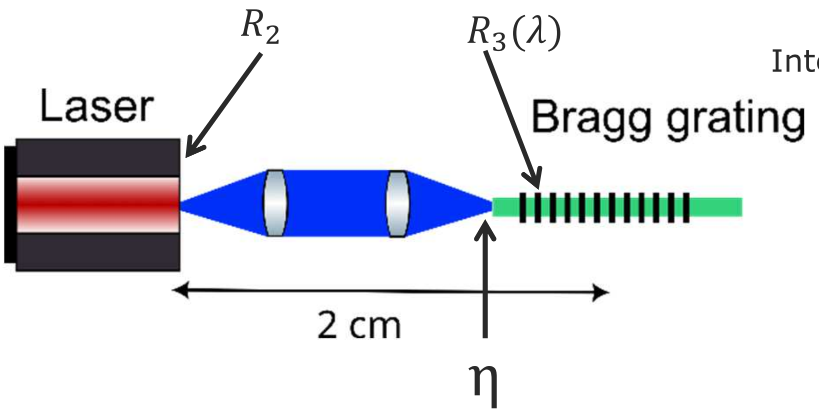
Fiber Bragg grating

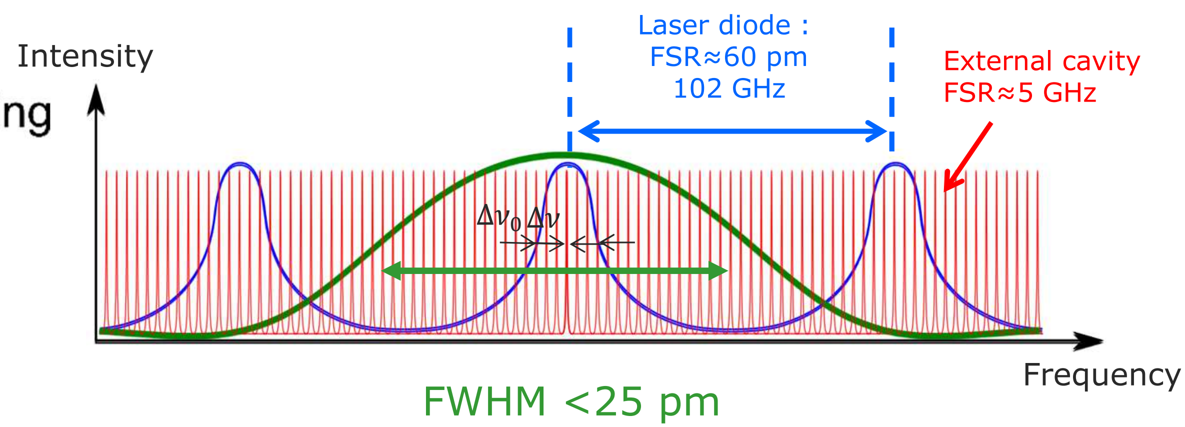


A. Congar *et al.*, OL (**46**) pp. 1077 (2021)



Axis 1: Design of the Fiber Bragg Grating Laser (FGL)





Single mode operation by self-injection locking

1/ Mode collapse *Laser diode longitudinal mode selection*

Bragg FWHM < Laser diode FSR

Single mode linewidth : $\Delta\nu_0$

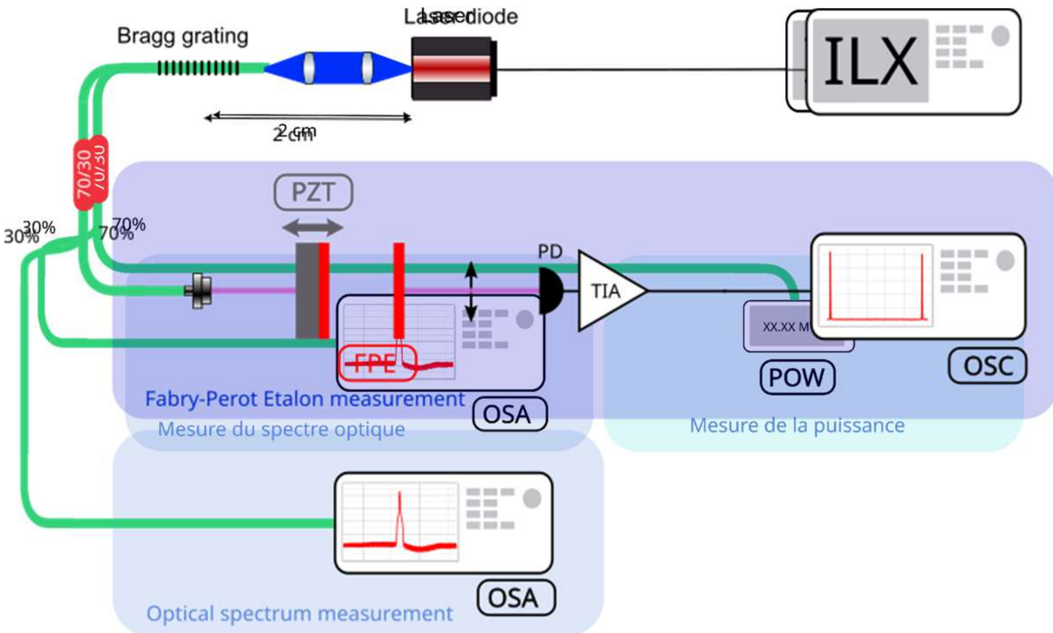
2/ Linewidth narrowing *Single mode laser emission*

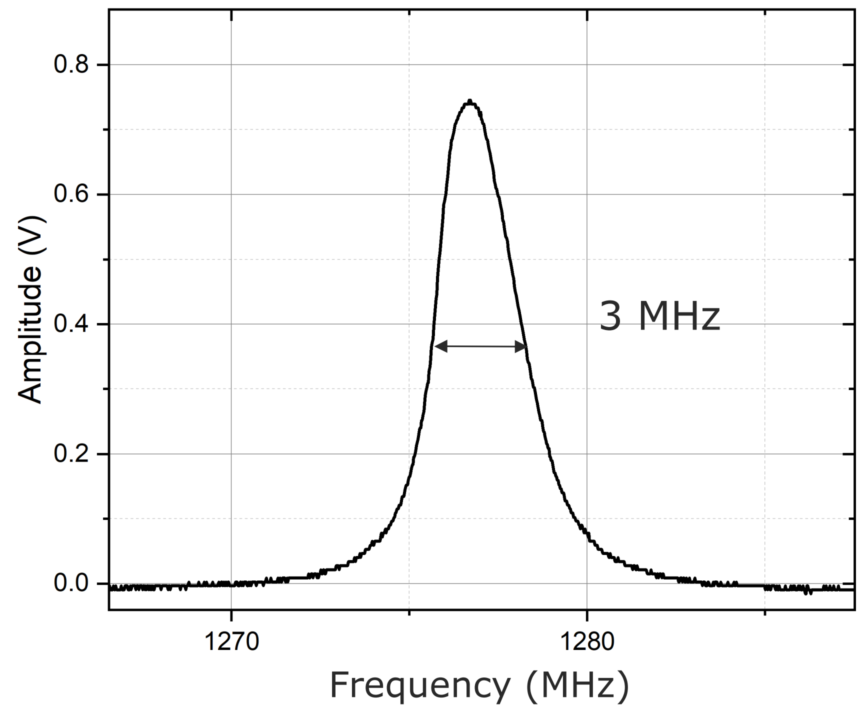
Short external cavity (2 cm) for large FSR (5 GHz)

Single frequency linewidth: $\Delta\nu = \frac{\Delta\nu_0}{(1+C)^2}$

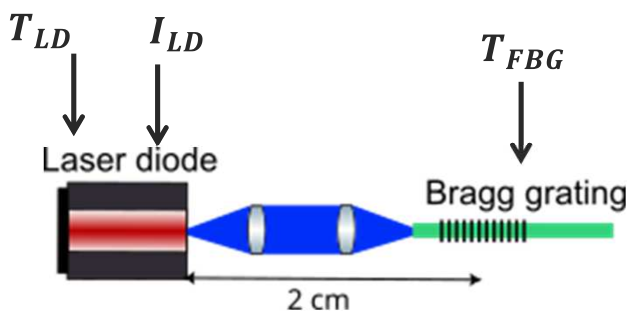
C feedback coefficient

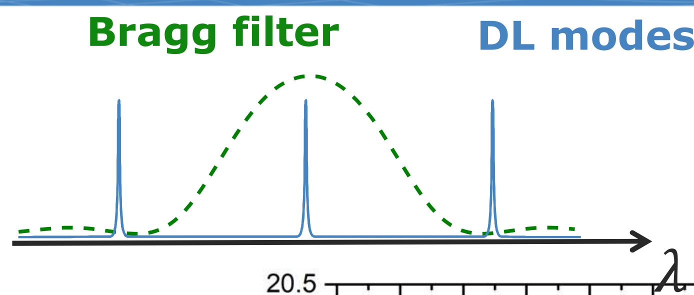
Axis 1: Spectral characterization of 459 nm FGL

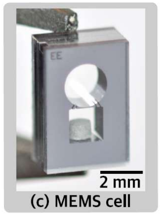




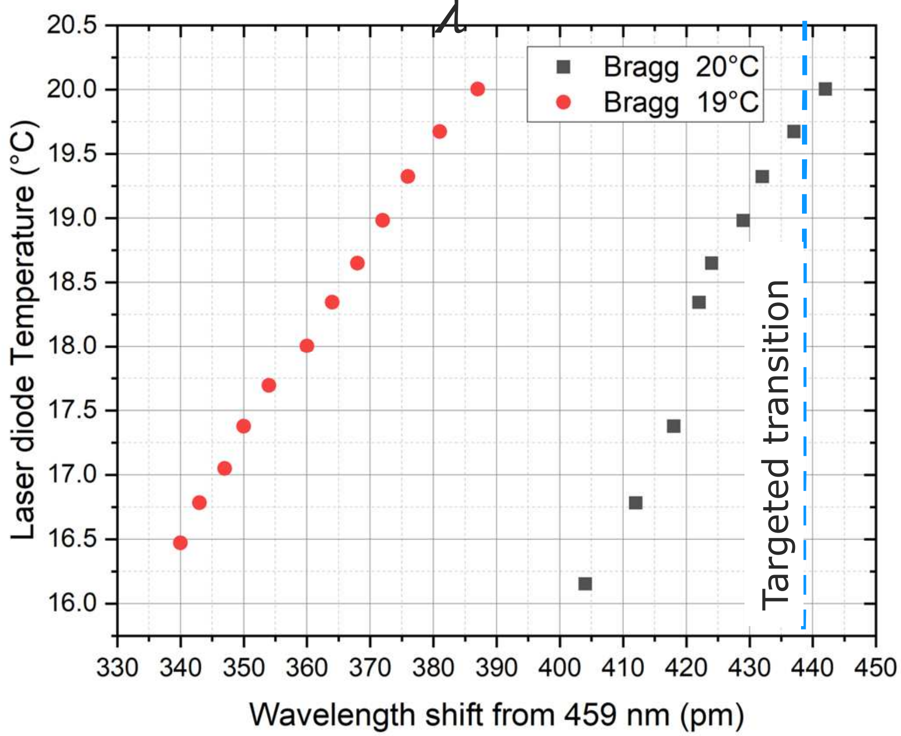
Axis 1: FGL tunability







- Coarse tuning by Bragg temperature shift
  - Laser diode mode hopping ($FSR \approx 60\ pm/°C$)
- Fine tuning by laser temperature shift
  - Wavelength shift $1{,}7\ GHz/0{,}1°C$
- Frequency modulation
  - Modulation frequency few 100 kHz for PDH
  - Scanning range $\approx 500\ MHz$



- Laser wavelength tunability to reach the atomic transition
- Laser wavelength modulation to implement PDH locking

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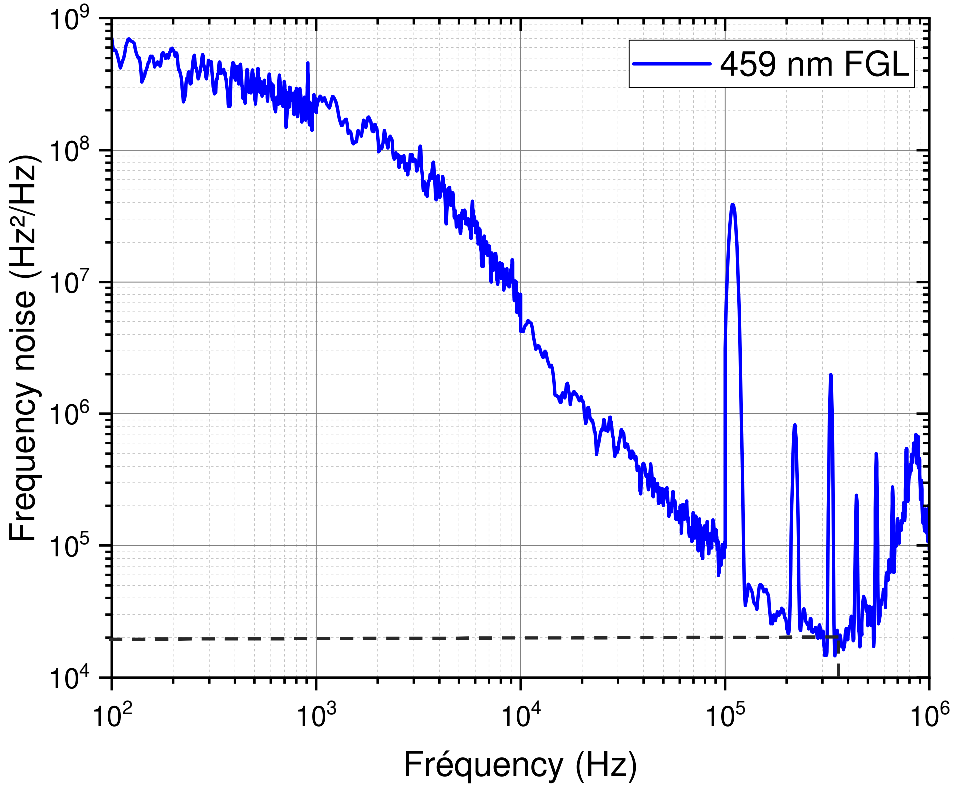
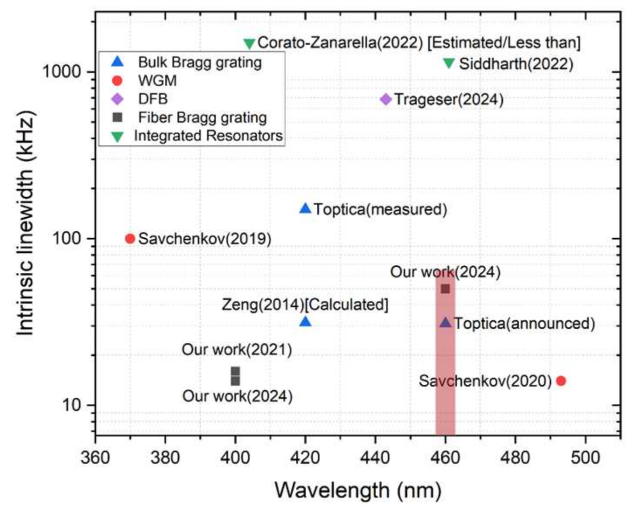
Axis 1: Frequency noise characterization



Integrated linewidth @ 10 ms : 2 MHz

Intrinsic linewidth : 50 kHz



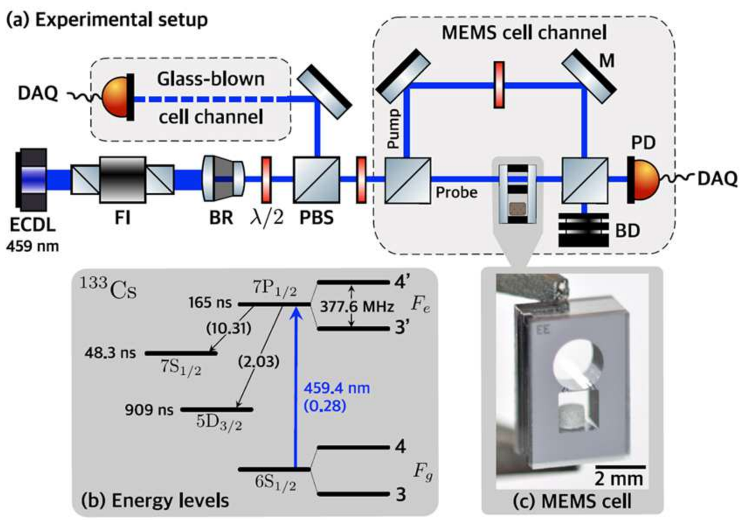
$S_{\Delta\nu}(300kHz) \approx 2 \times 10^4\ Hz^2/Hz$

compatible with $\sigma(1s) \approx\ 10^{-13}$

➢ Low frequency noise (intermodulation effect)

Axis 2: Spectroscopy of the Cs $6S_{1/2}$-$7P_{1/2}$ transition

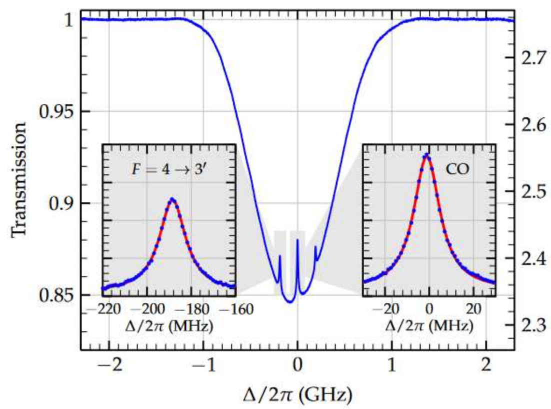
First spectroscopy setup



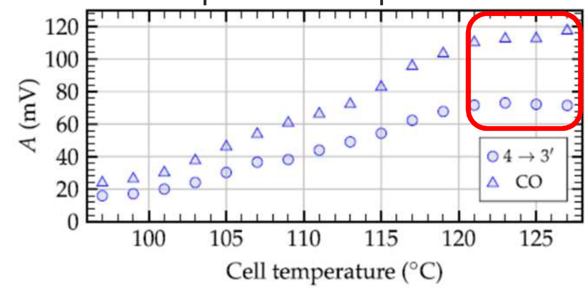
Separared Pump-probe beams

E. Klinger et al., Opt. Lett. 49, 8 (2024)

Doppler-free spectrum

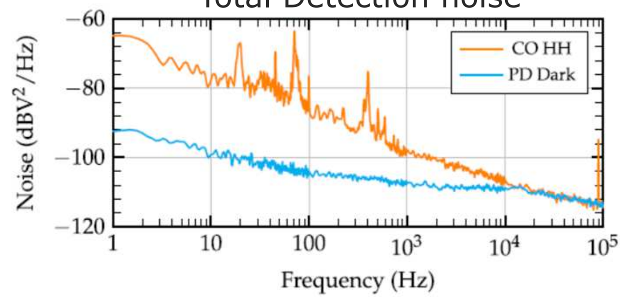


Impact of temperature



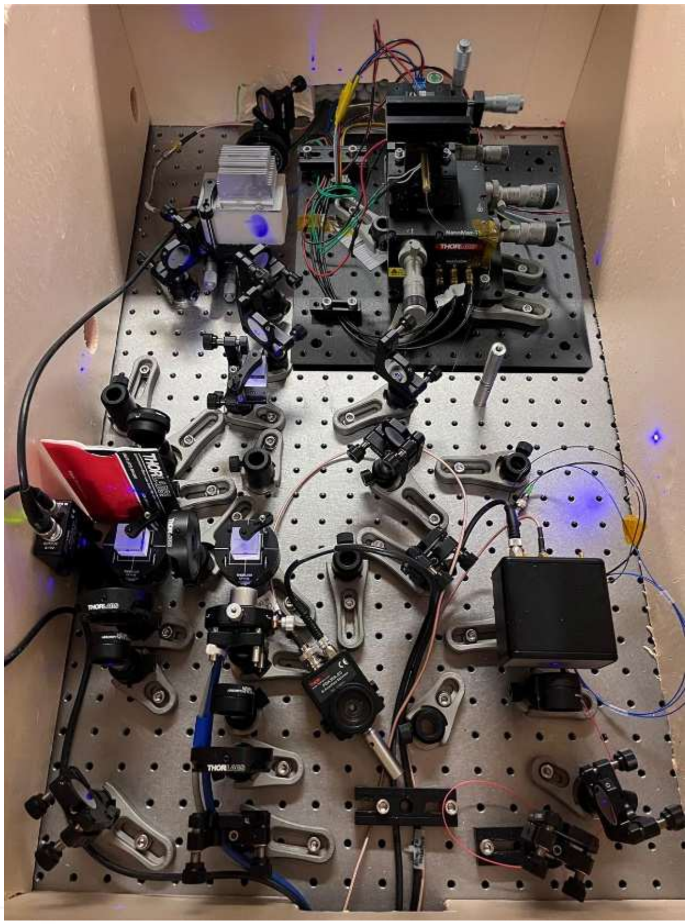
Optimum at ~ 120 °C

Total Detection noise



Stability prediction : **3.5 x 10^{-13} at 1s**
(with this first cell)

Axis 1 + Axis 2: Blue laser FOTON + Microcell



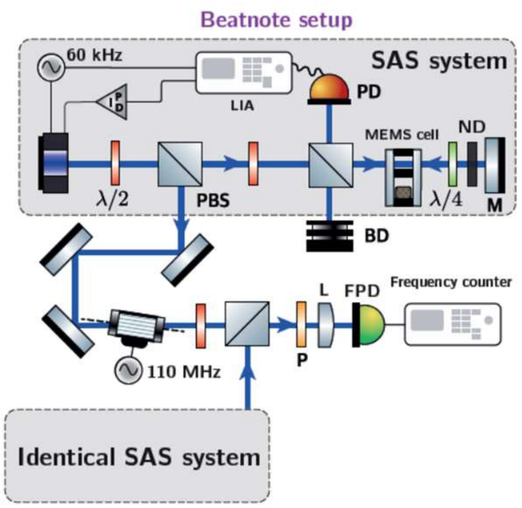
1 week visit of Georges at FEMTO-ST
(mid-June 2024)

- Move the laser set-up from Foton to Femto
- Integration on the laser on FEMTO-ST set-up
- Issue of mechanical noise

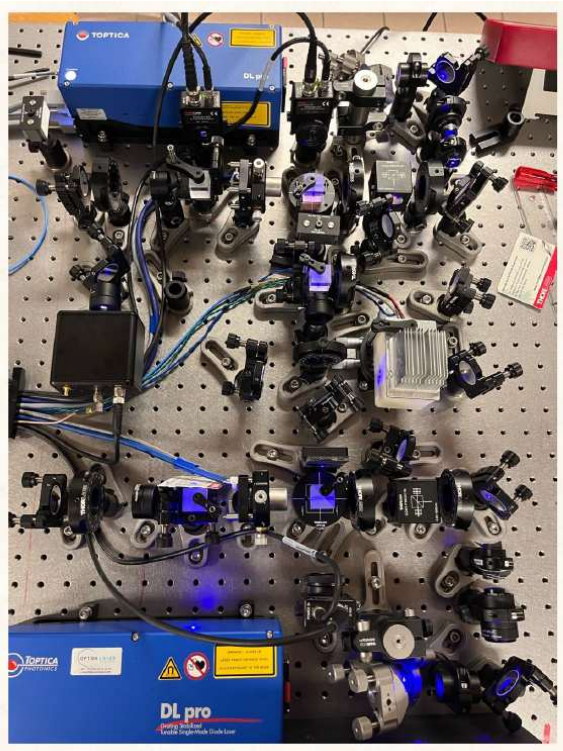
Not yet possible to resolve Cs lines

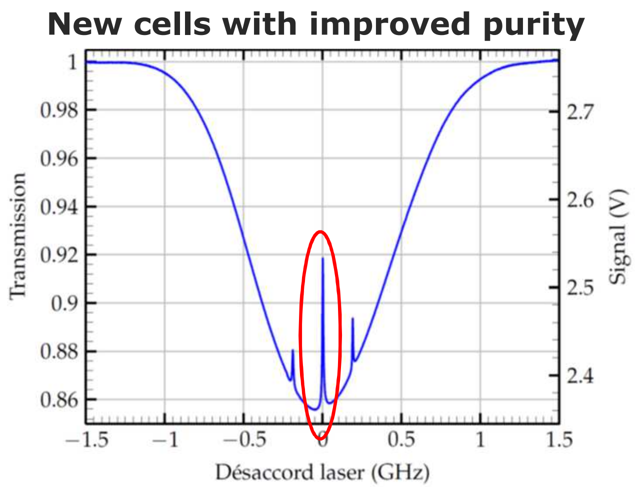
First stability tests: 2 microcell-stailized ECDLs

Reception of a second blue ECDL at FEMTO-ST early September 2024 (9 months delivery…)



2 ECDLs, each locked to Cs transition
Simplest retro-reflected configuration
AOM used to create a beatnote (110 MHz)

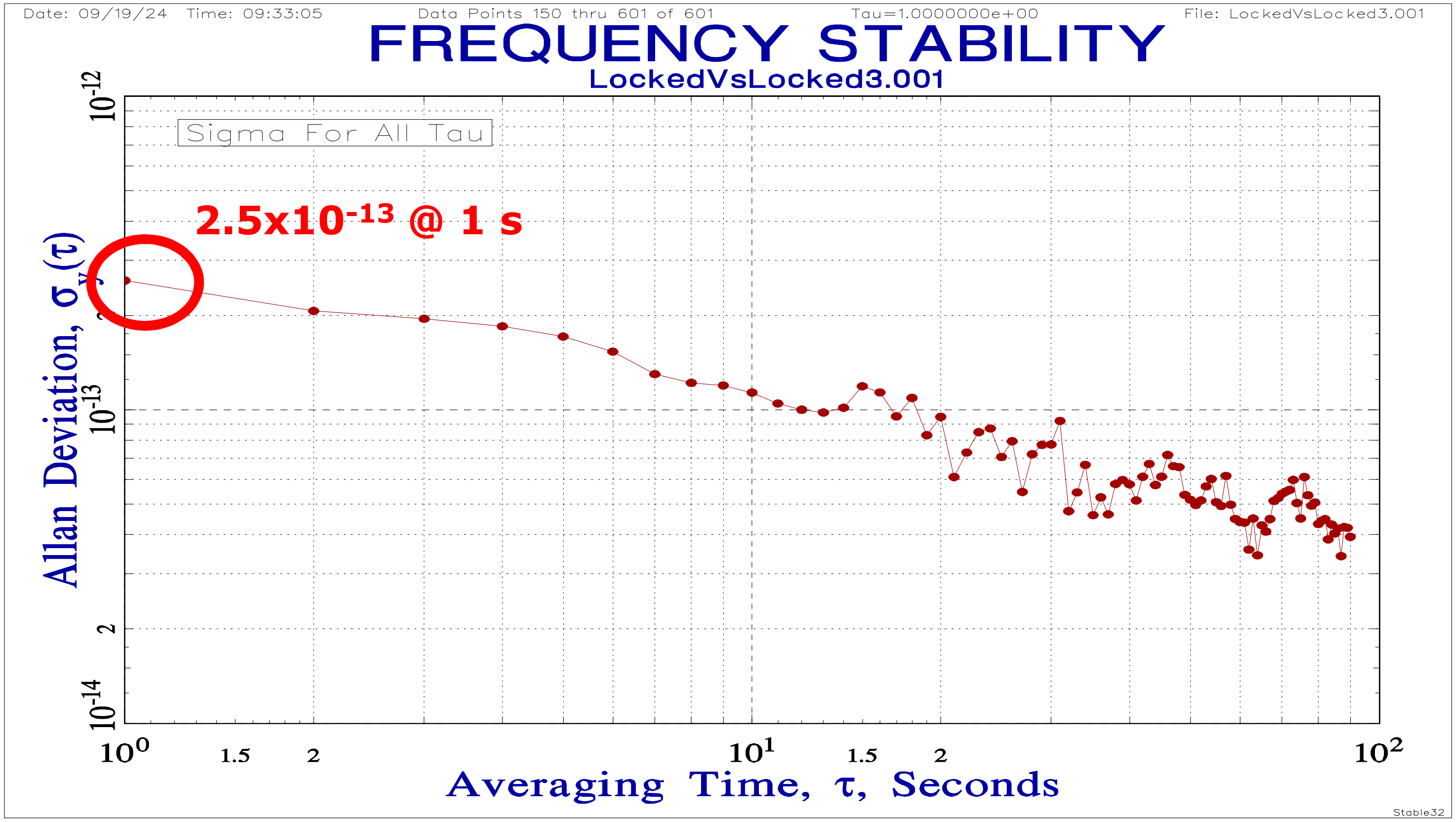




Improved signal and linewidth

Very first (and very short!) stability tests

Laser beatnote Allan deviation



1 single laser
(if both contribute equally)

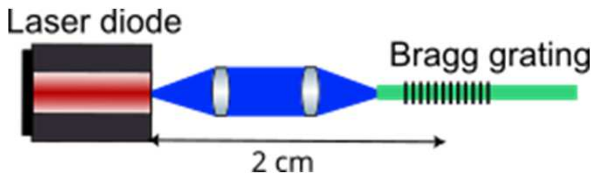
1.8×10^{-13} @ 1 s

Encouraging results (to be pursued!)

Conclusions and perspectives

➢ Compact self-injected Fiber Bragg Grating laser diode in the UV-Blue range

- **Frequency noise level compatible with 10^{-13} stability reached** => $S_{\Delta\nu}(300\text{kHz}) \approx 2 \times 10^4\ \text{Hz}^2/\text{Hz}$
- Coarse and fine tuning to address specific optical frequencies
- PDH modulation possible



➢ Cs microcell technology and metrology

- Sub-Doppler spectroscopy of the Cs atom $6S_{1/2} - 7P_{1/2}$ transition in a MEMS cell
- Impact of key experimental parameters (cell T, laser power, etc.)
- **Short-term stability in the low 10^{-13} range at 1 s** with commercial ECDLs

➢ Perspectives

- Pursued efforts to make FOTON laser + FEMTO-ST microcell work together (increase robustness)
- Frequency metrology of the Cs microcell optical reference (PhD C. Rivera, CNES/UFBFC)

Thank you for your attention

Projet LEILA
(2023-2024)