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

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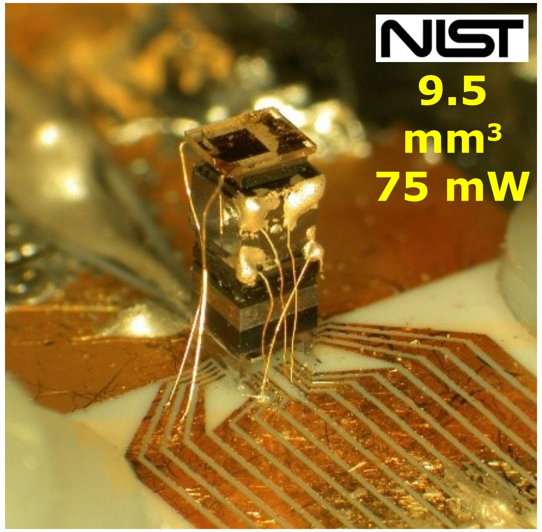
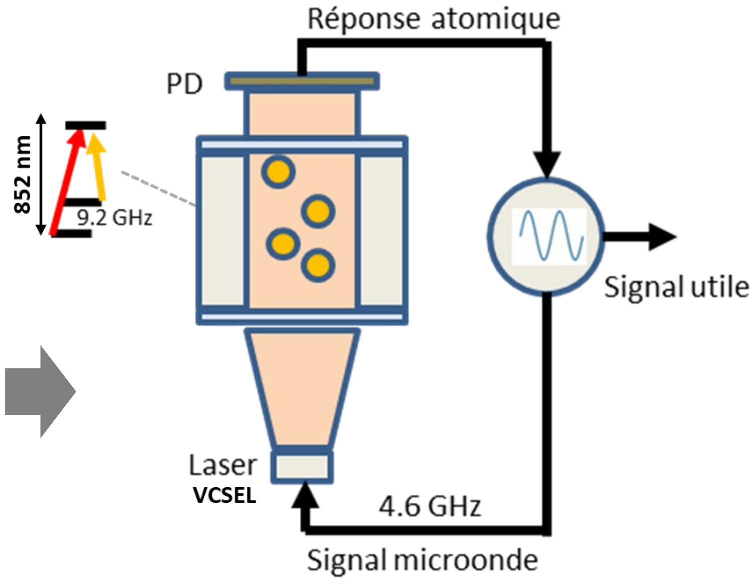
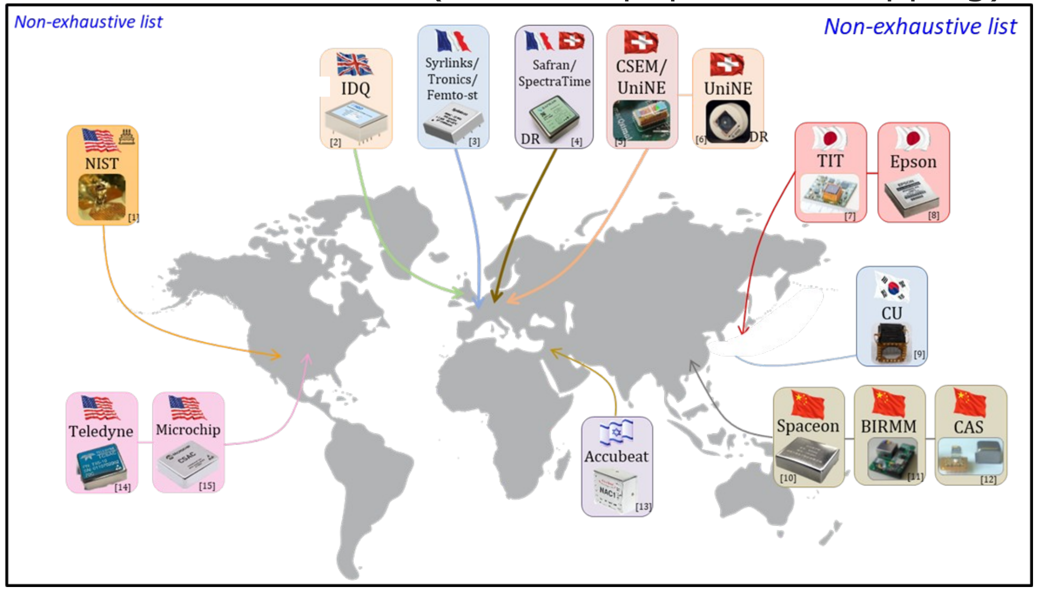
Context: Chip-Scale Atomic Clocks



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 cm^3
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

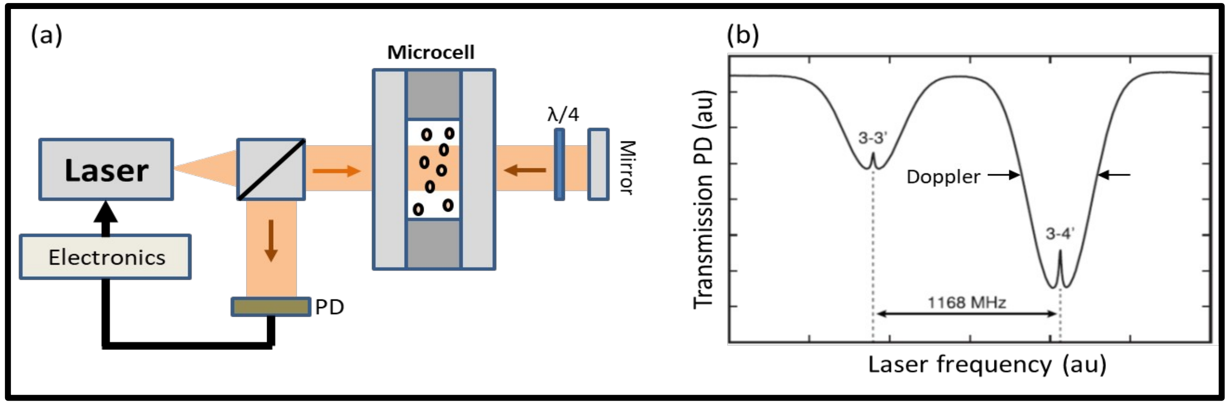
Increase the SNR

Low-noise lasers

Detect high-signals

Sub-Doppler spectroscopy techniques

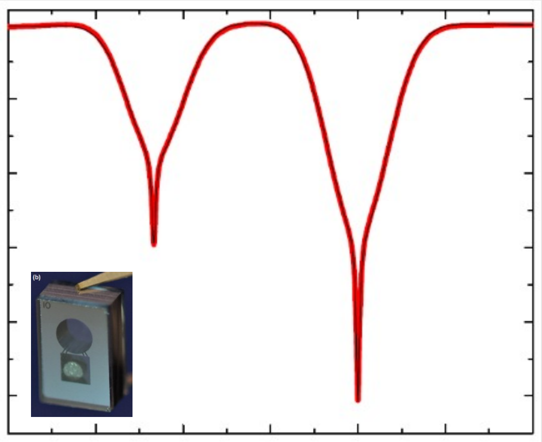
Hot vapor interacts with two counter-propagating fields: Doppler-free resonances



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)



femto-st SCIENCES & TECHNOLOGIES

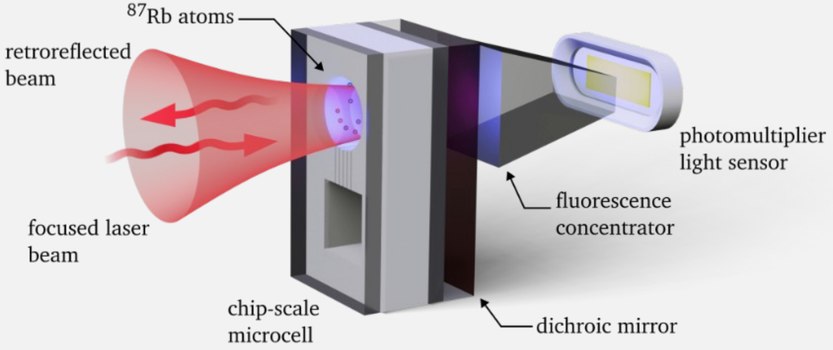
$3\times10^{-13}\ \tau^{-1/2}$ up to 100 s

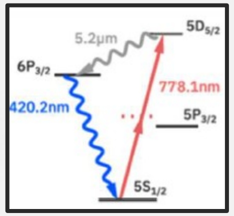
A. Gusching et al., Opt. Lett. 48, 6, 1526 (2023)

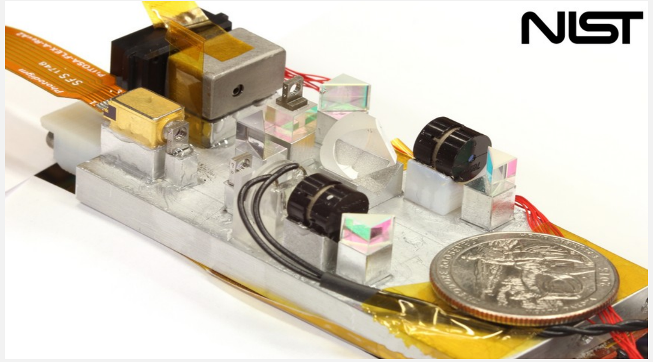
Requires a microwave-modulated optical field (EOM)

Complex architecture

Two-photon transition in Rb atom (778 nm)







$1.8\times10^{-13}\ \tau^{-1/2}$ up to 100 s

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

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$3\times10^{-13}\ \tau^{-1/2}$ 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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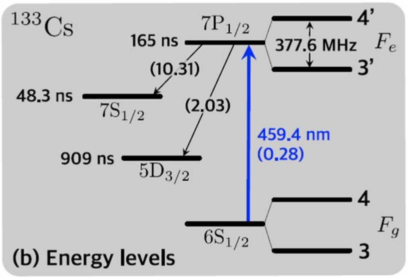
INSTITUT foton

LEILA motivations: near a near-UV microcell optical reference

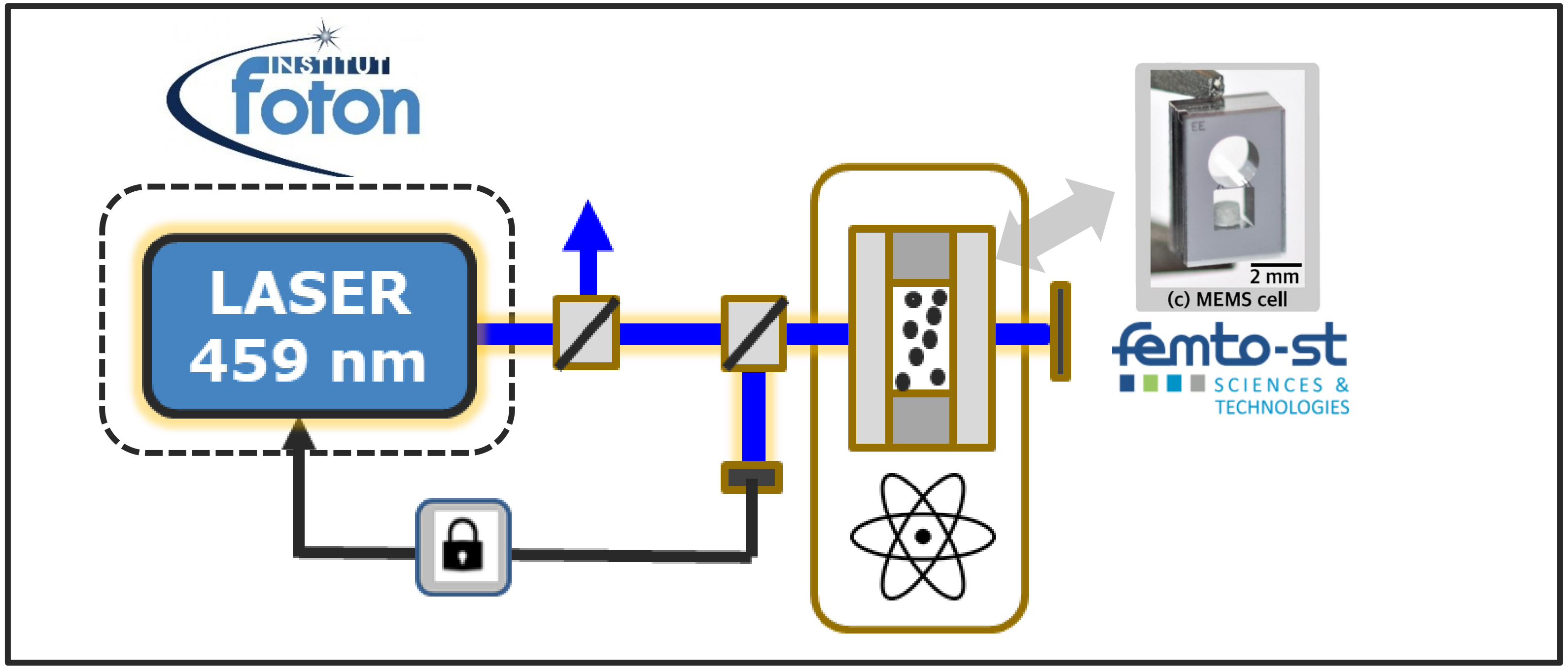
What about directly probing a blue transition ?

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



(b) Energy levels

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

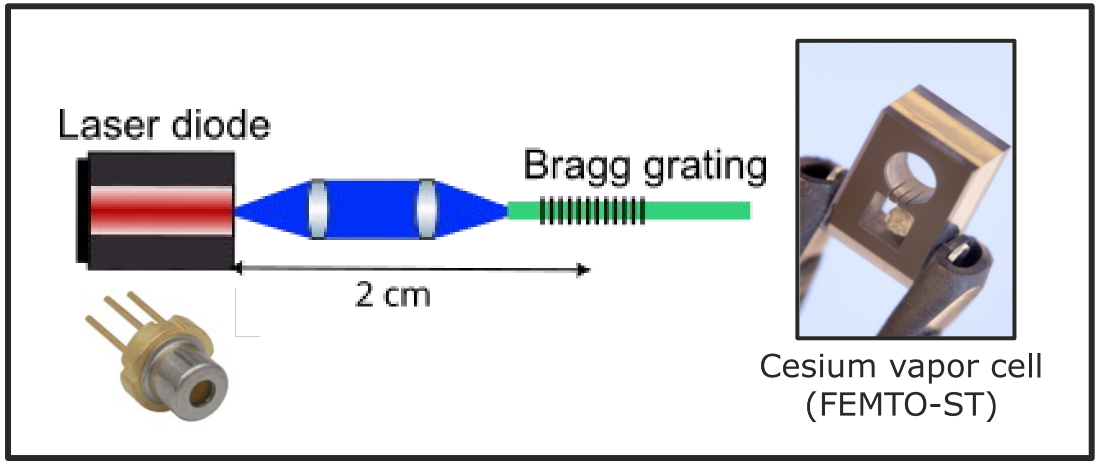


Axis 1: Blue laser (FOTON)

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)

$$\sigma(1s) = \frac{\sqrt{S_{\Delta\nu}(2fm)}}{2\nu_0} \Rightarrow \sigma(1s) = 10^{-13} \Rightarrow S_{\Delta\nu}(2fm) < 2\times10^4\,Hz^2/Hz$$

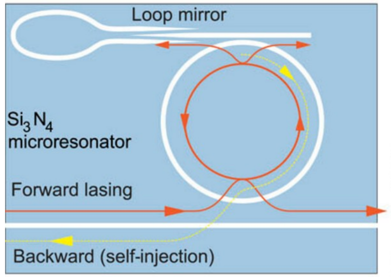
C. Audoin et al. IEEE TIM 1991

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

Diffraction grating

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

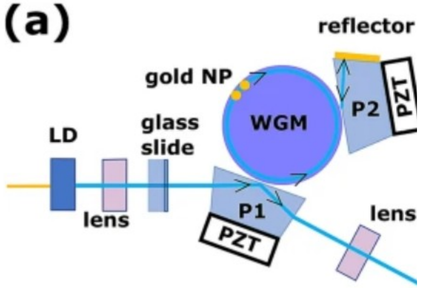
Integrated resonators



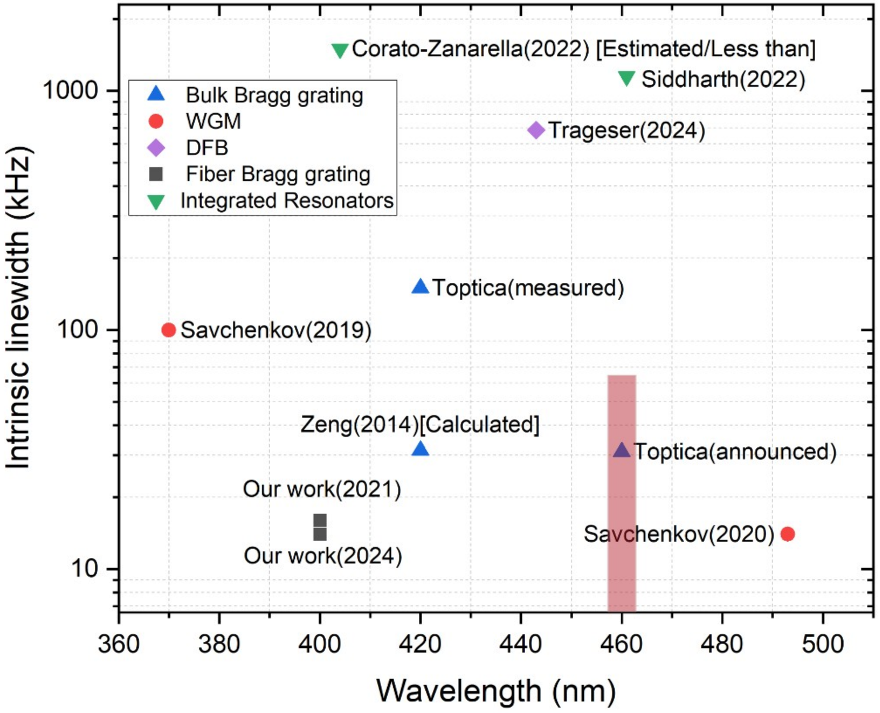
A. Siddharth *et al.* APL Photonics **7** L046108 (2022)

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

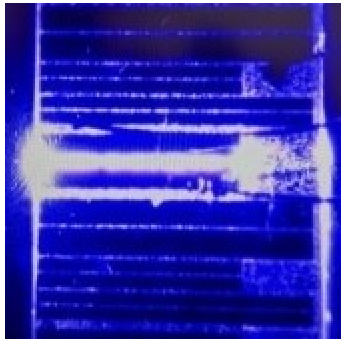
Whispering gallery mode (WGM) resonator



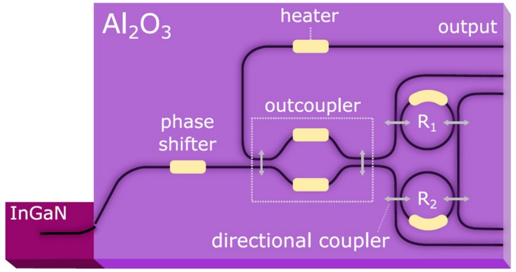
A.A. Savchenkov, *et al. Sci Rep* **10**, pp 16494 (2020)



Distributed feedback laser

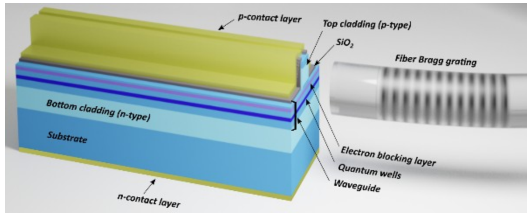


E. Trageser et al. OE **32**, pp 23372 (2024)



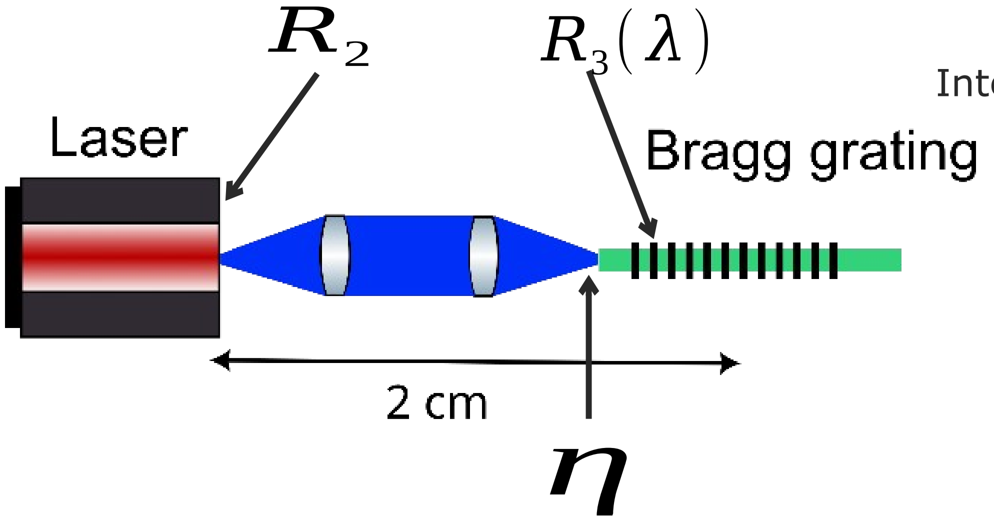
C. Franken et al. Arxiv 2302.11492 (2023)

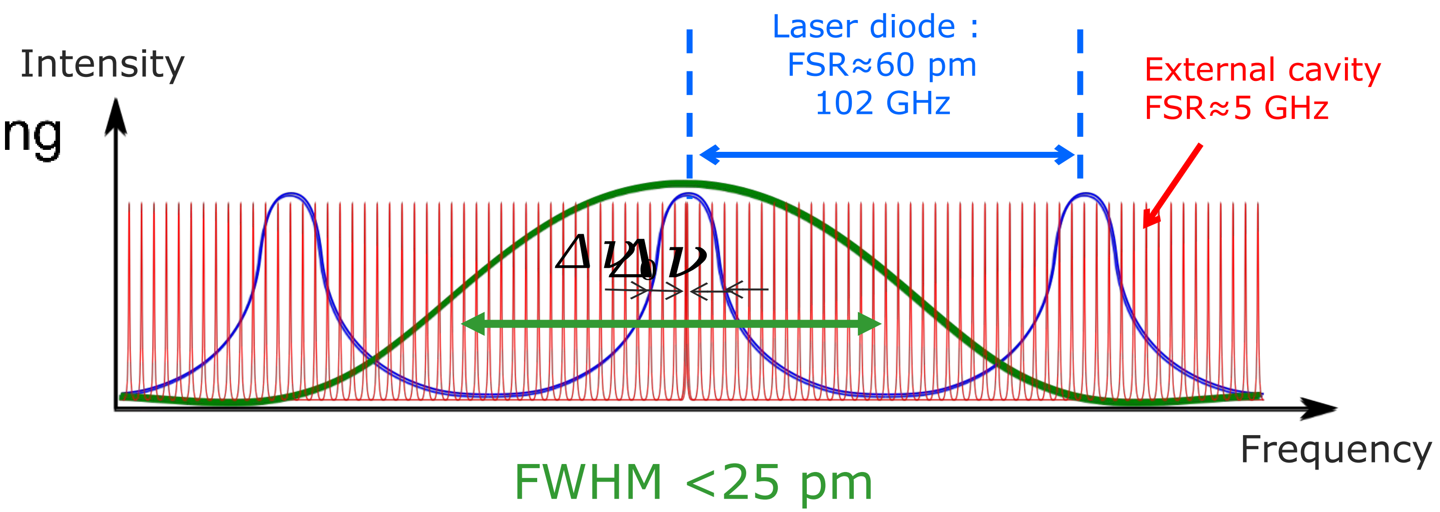
Fiber Bragg grating



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

2/ Linewidth narrowing *Single mode laser emission*

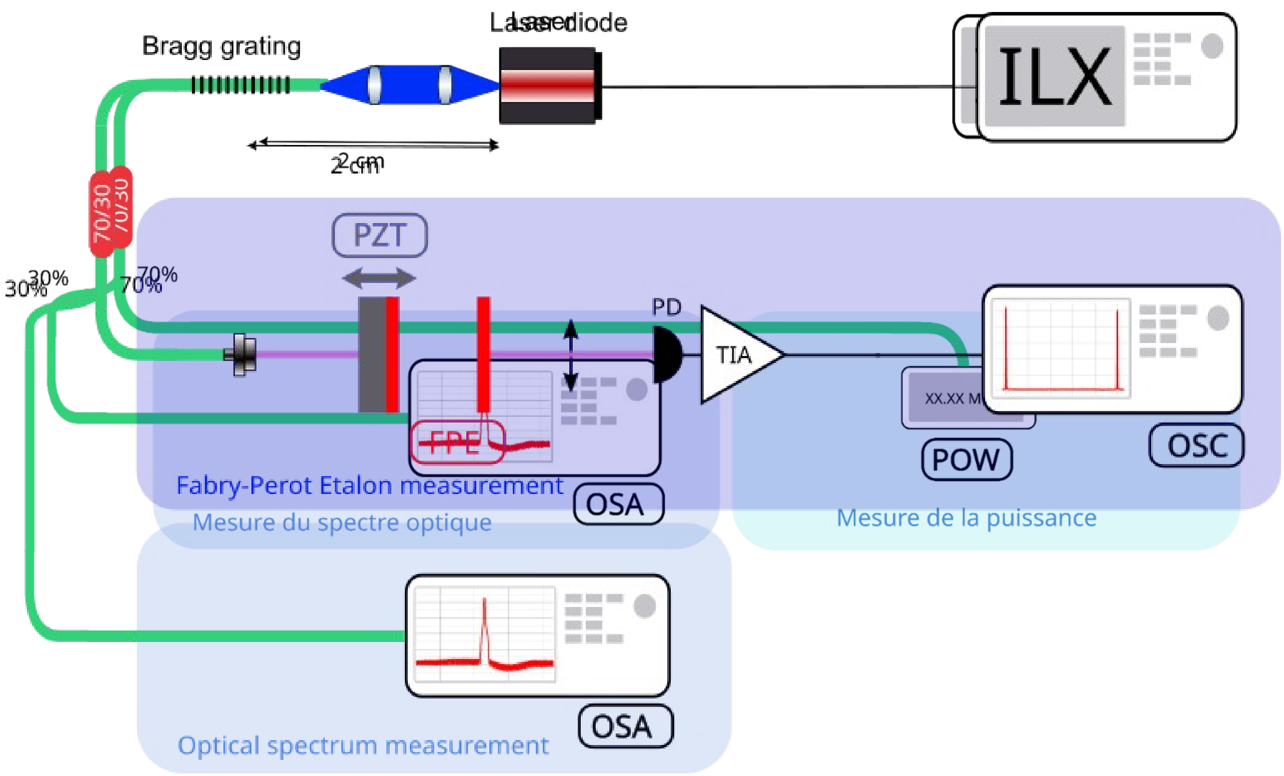
Short external cavity (2 cm) for large FSR (5 GHz)

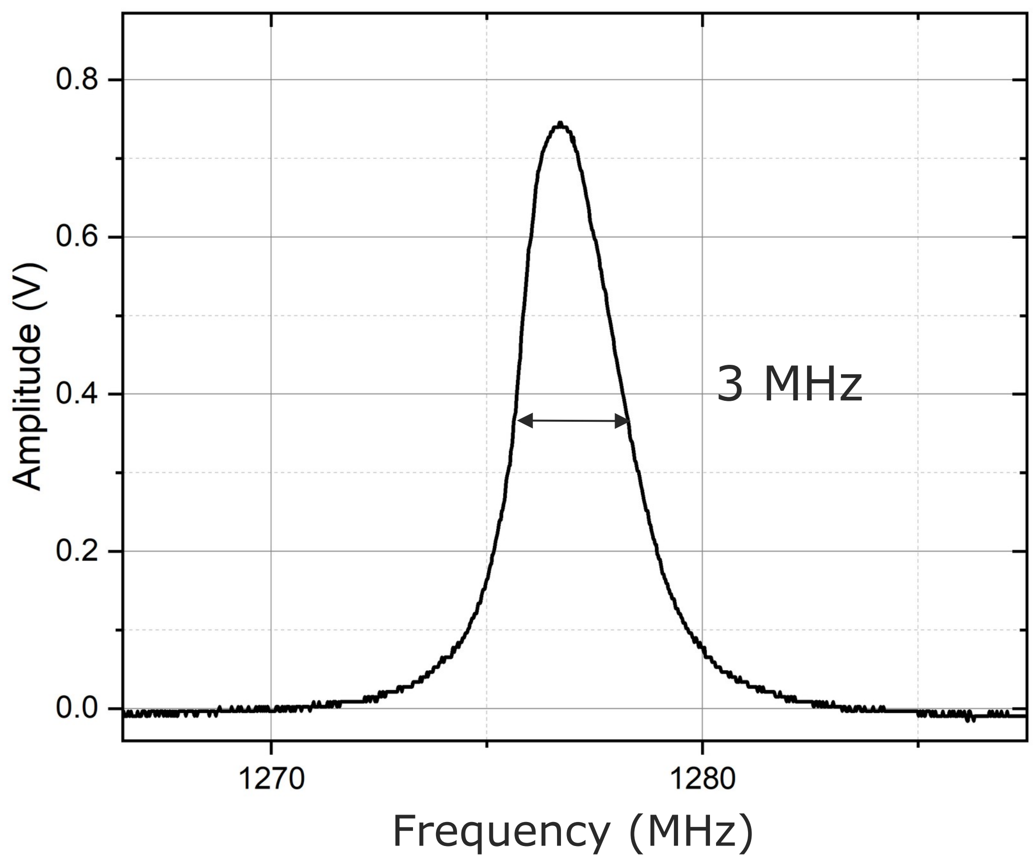
Single mode linewidth :

Single frequency linewidth:

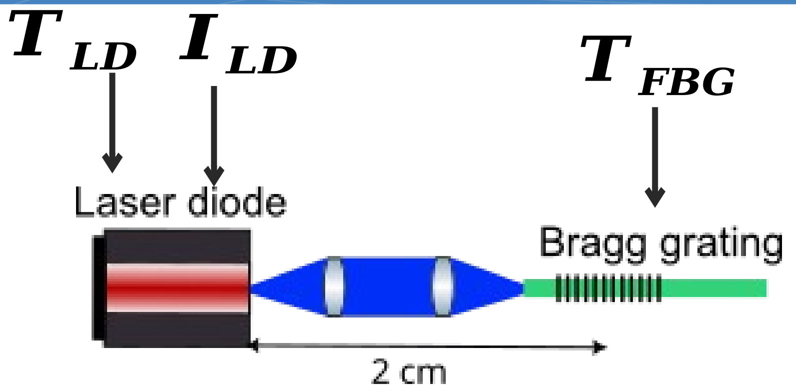
feedback coefficient

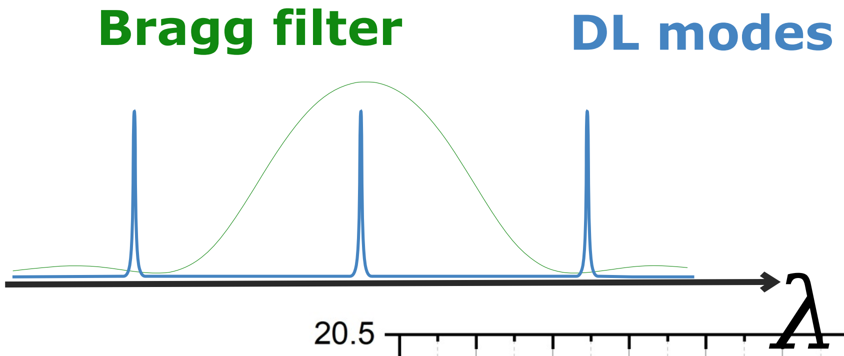
Axis 1: Spectral characterization of 459 nm FGL

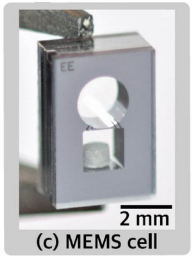




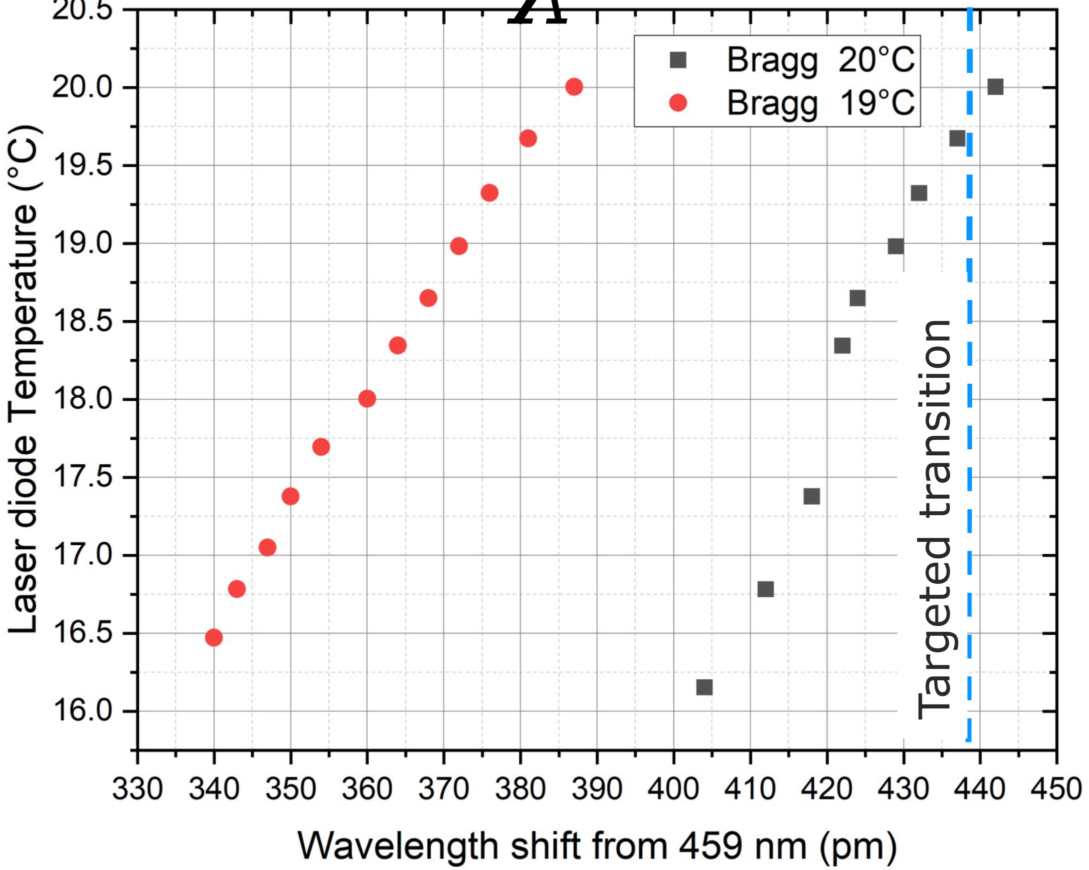
Axis 1: FGL tunability







- Coarse tuning by Bragg temperature shift
  - Laser diode mode hopping (
- Fine tuning by laser temperature shift
  - Wavelength shift /
- Frequency modulation
  - Modulation frequency few 100 kHz for PDH
  - Scanning range



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

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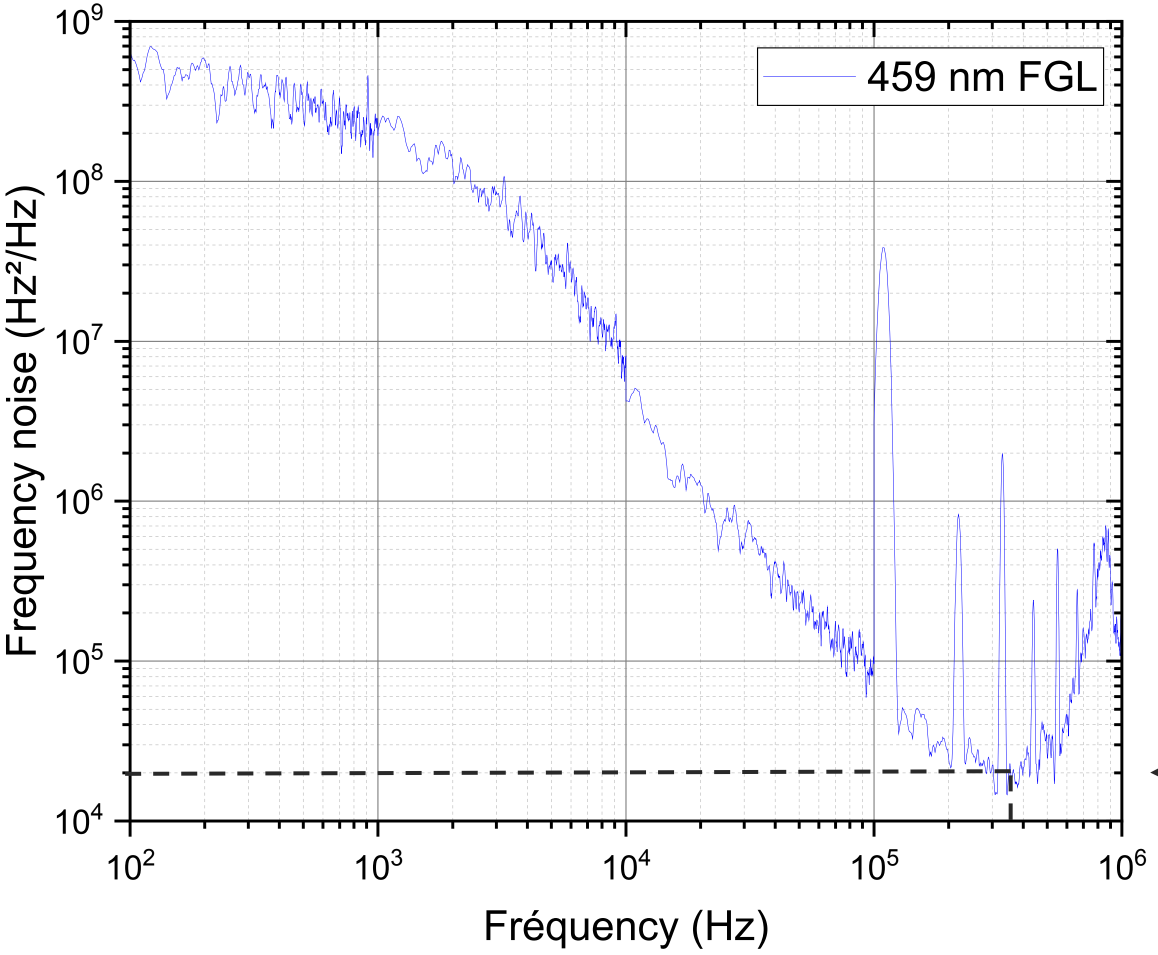
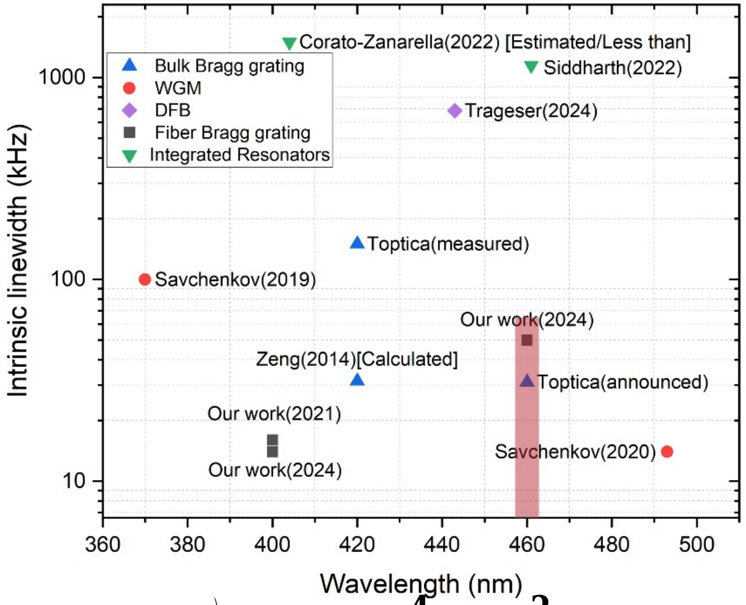
Axis 1: Frequency noise characterization



Integrated linewidth @ 10 ms : 2 MHz

Intrinsic linewidth : 50 kHz



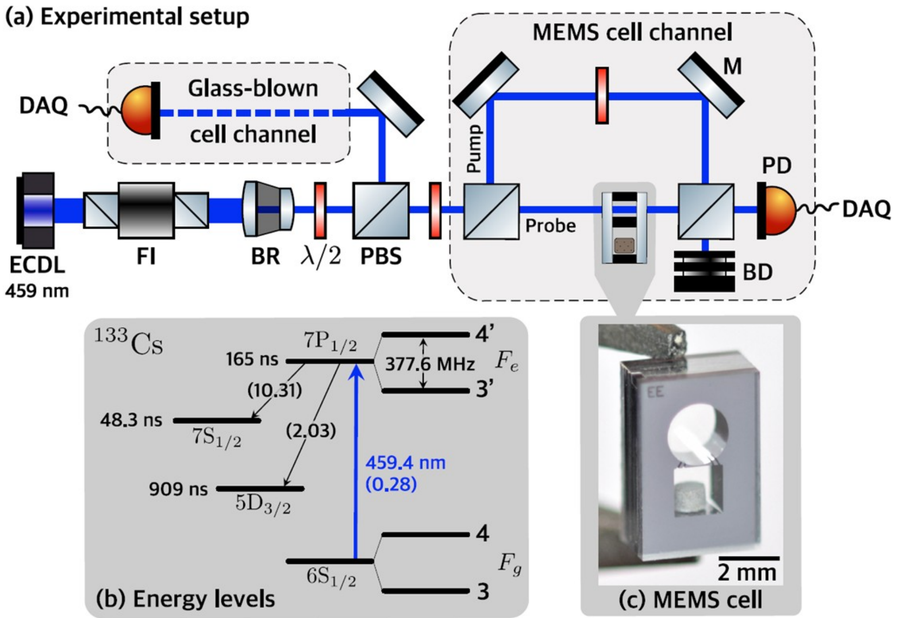
$$S_{\Delta\nu}(300\,kHz) \approx 2 \times 10^4\, Hz^2/Hz$$

compatible with

➢ Low frequency noise (intermodulation effect)

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

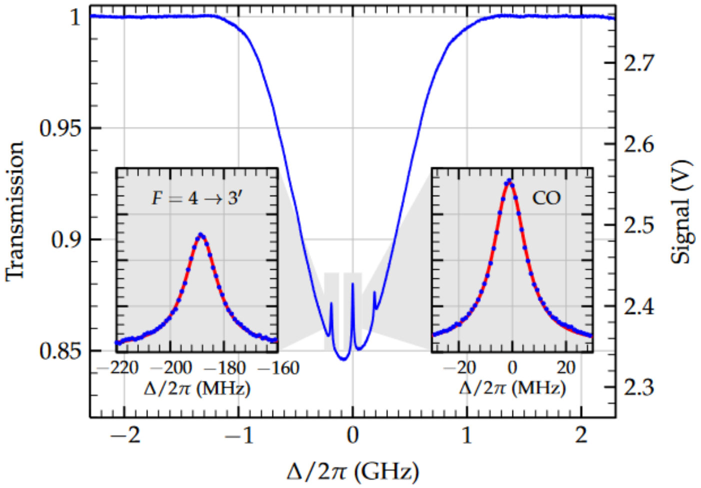
First spectroscopy setup



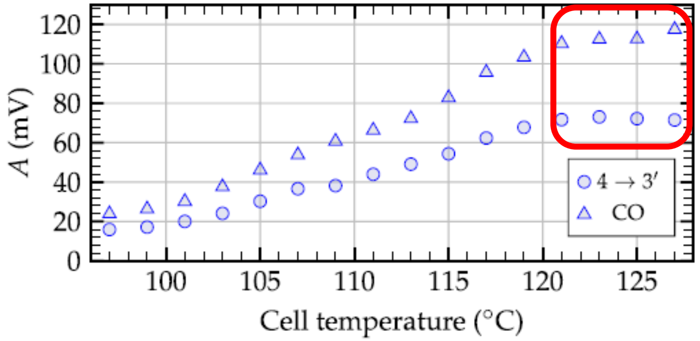
Separared Pump-probe beams

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

Doppler-free spectrum

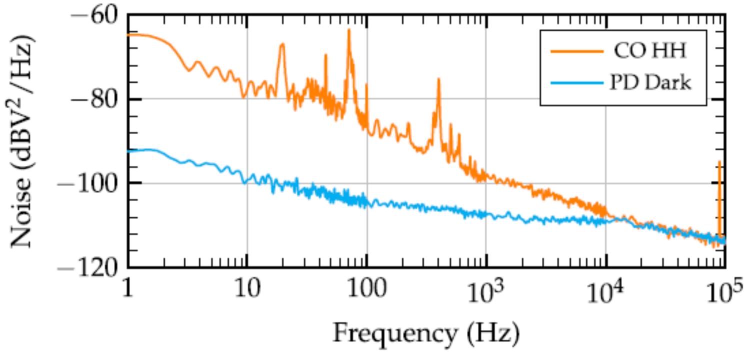


Impact of temperature



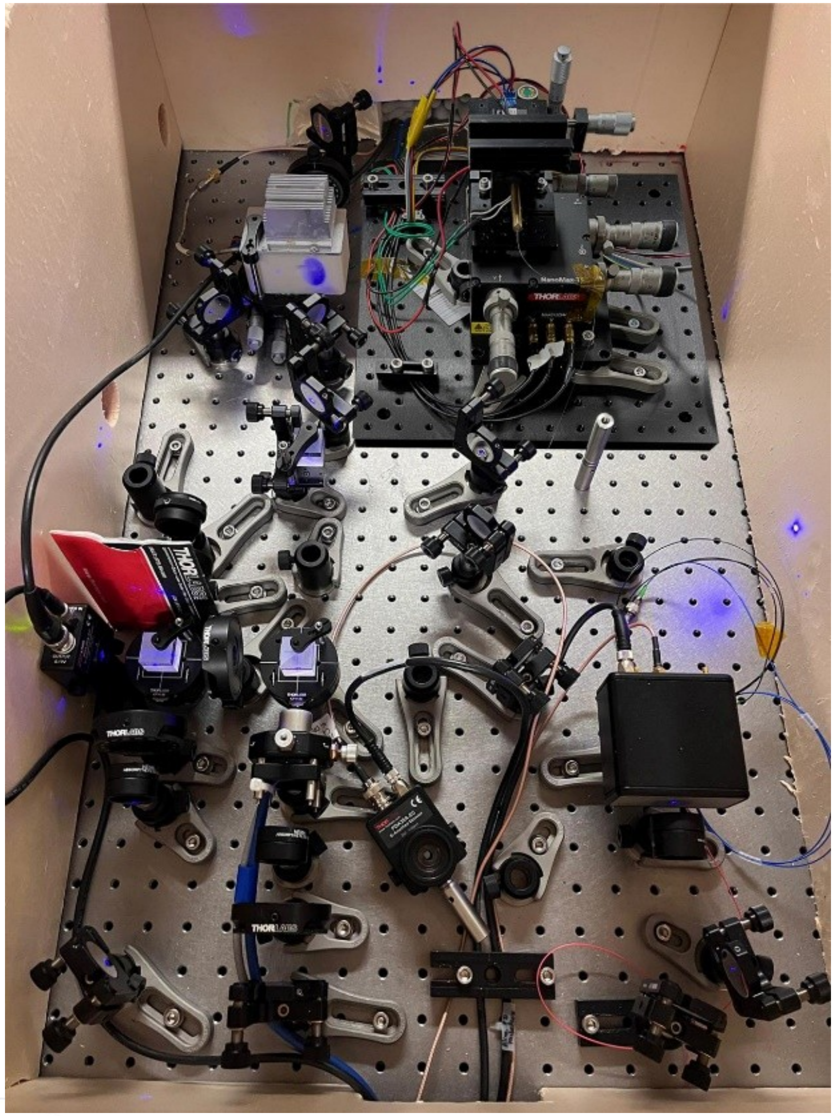
Optimum at ~ 120 °C

Total Detection noise



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

Axis 1 + Axis 2: Blue laser FOTON + Microcell



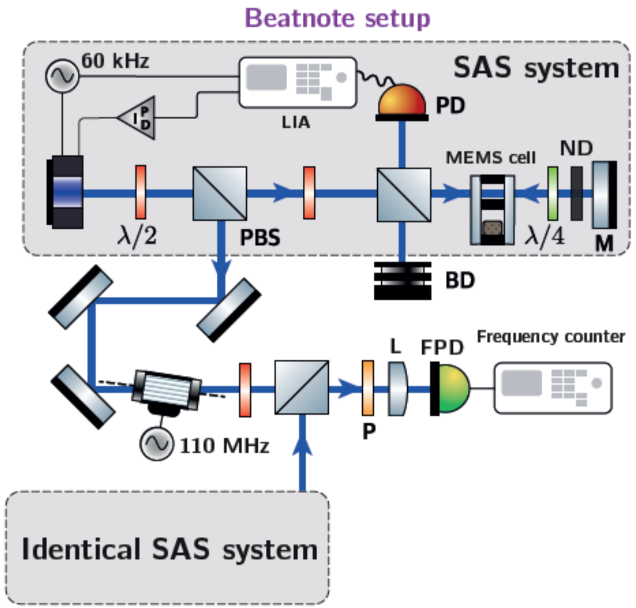
1 week visit of Georges at FEMTO-ST
(mid-June 2024)

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

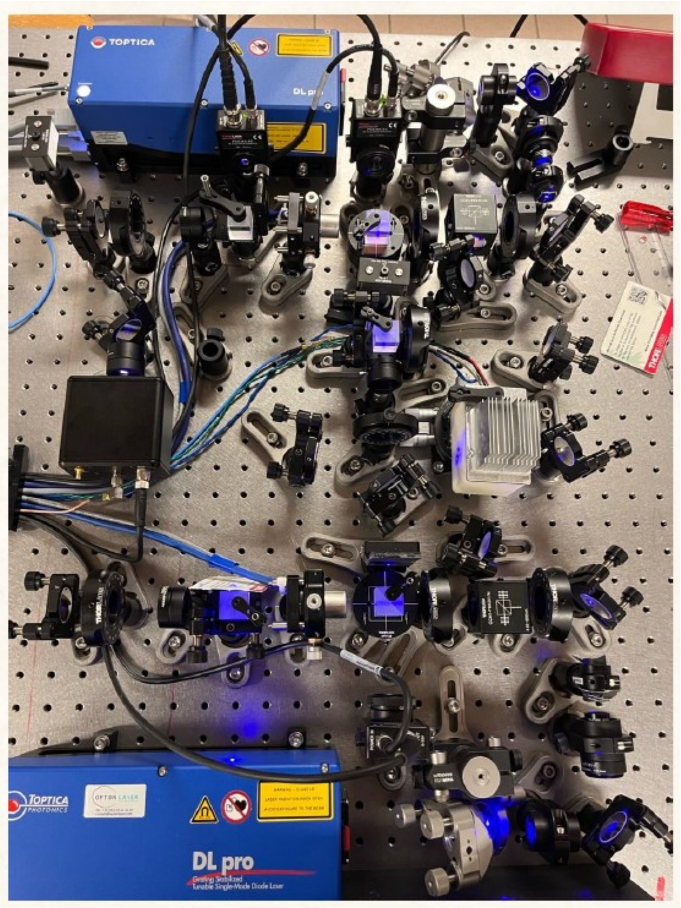
Not yet possible to resolve Cs lines

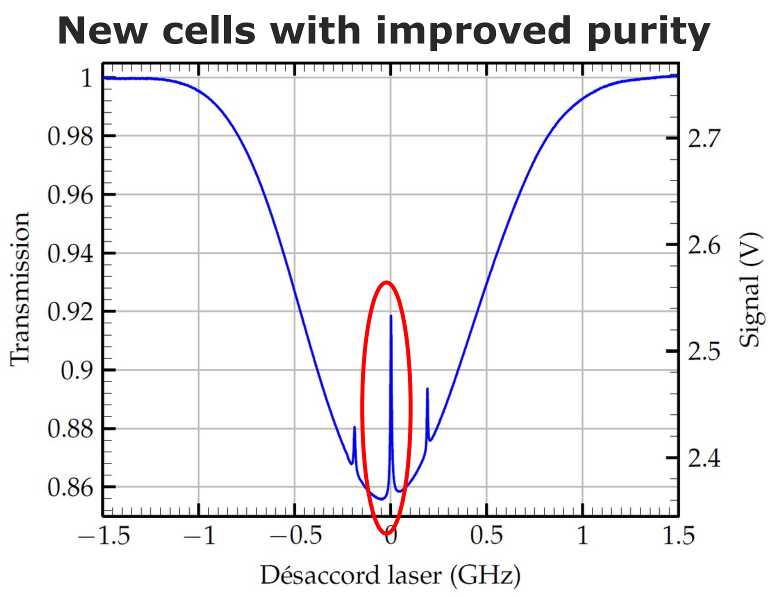
First stability tests: 2 microcell-stailized ECDLs

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)

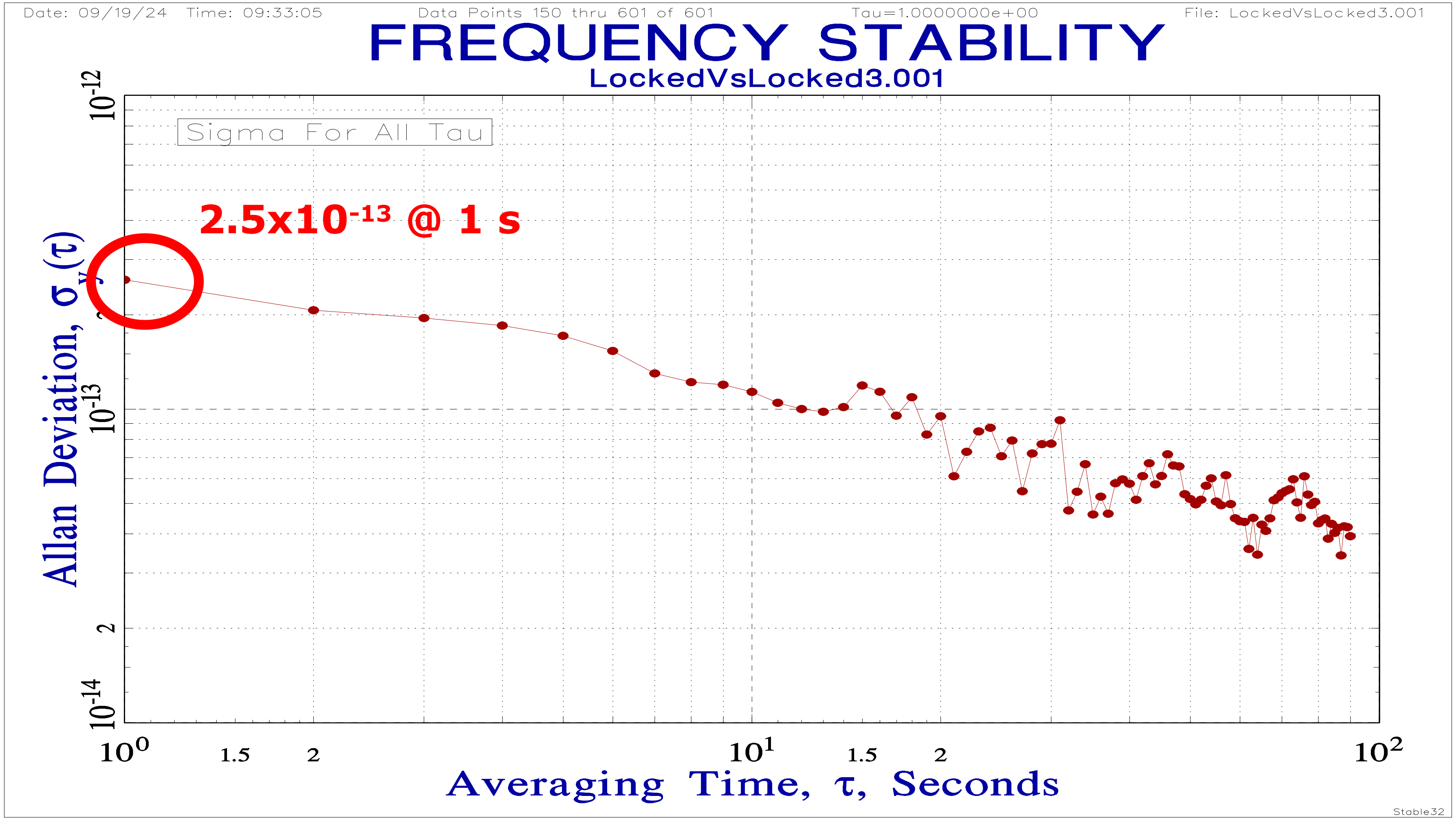




Improved signal and linewidth

Very first (and very short!) stability tests

Laser beatnote Allan deviation



1 single laser
(if both contribute equally)

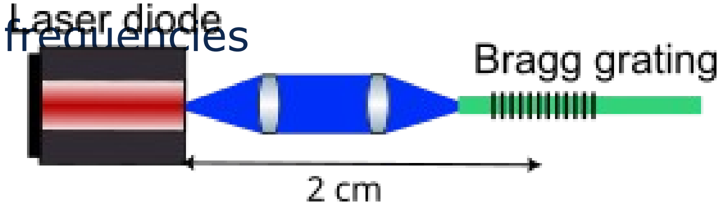
1.8×10^{-13} @ 1 s

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** =>
- Coarse and fine tuning to address specific optical frequencies
- PDH modulation possible



➢ **Cs microcell technology and metrology**

- Sub-Doppler spectroscopy of the Cs atom 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)

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Agence Nationale de la Recherche ANR

Why atomic clocks ?

> Navigation, sensing, communication

Which type of compact atomic clocks ?

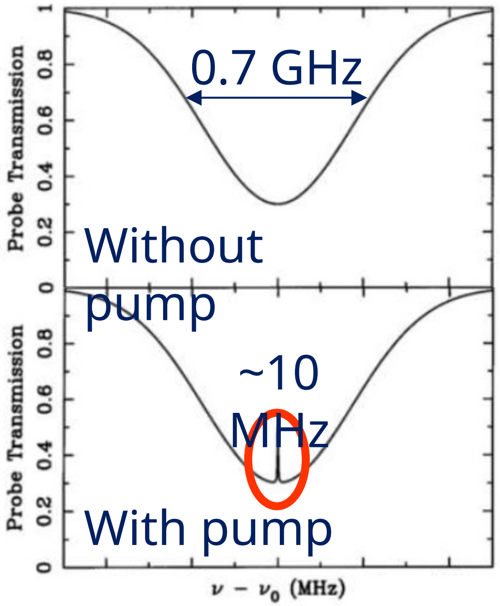
> Commercially available atomic clocks based on µwave interrogation of the atomic transition

> Possible improvement of the stability (by ~10³) by using optical interrogation of the atom

$$\sigma_y(1s) = \frac{\Delta\nu}{\nu_0} * \frac{1}{S/N}$$

...but minimizing the noise

Towards shorter wavelengths



Simple architecture:

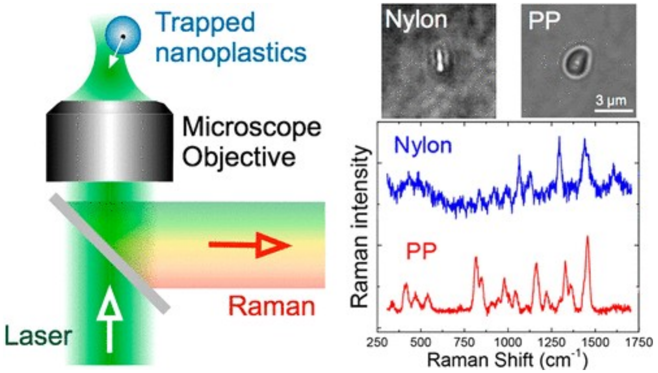
- No need of ultra-high vacuum technologies

- No need of cooling (Hot Cs vapor used)

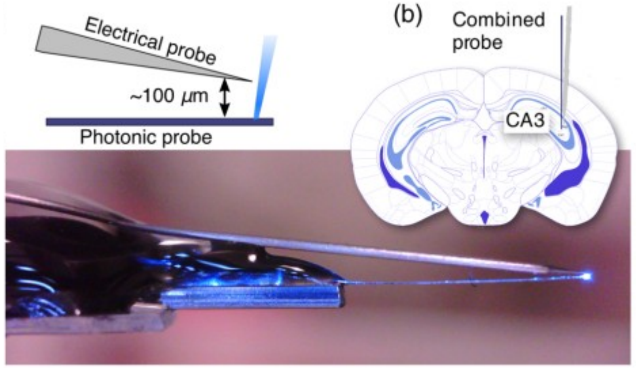
But request compact low noise pump laser

Blue/near-UV applications :

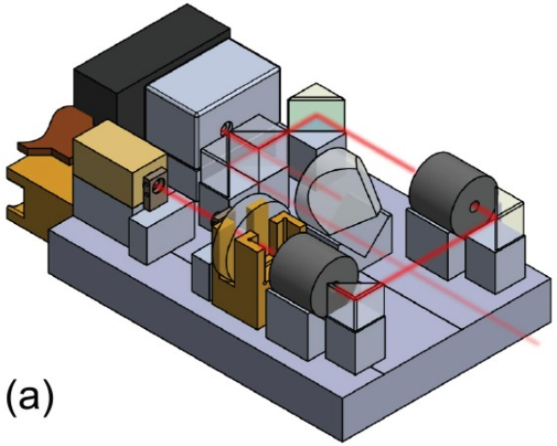
- Underwater LiDAR (water transparency)
- Chemical/bio sensing (Raman or fluorescence)
- Optogenetics (optical activation of neuronal cells)
- Atomic clocks (addressing atomic transitions)



Environ. Sci. Technol. 53, 15 (2019)



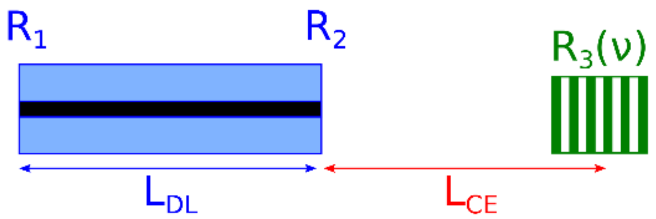
Neurophoton. 4, 011002 (2016)



Opt. Exp. (28), 17, 24710 (2020)

Development and integration in new commercial products require reduction of size, weight and power consumption **Need for compact narrow linewidth laser (<100 kHz)**

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



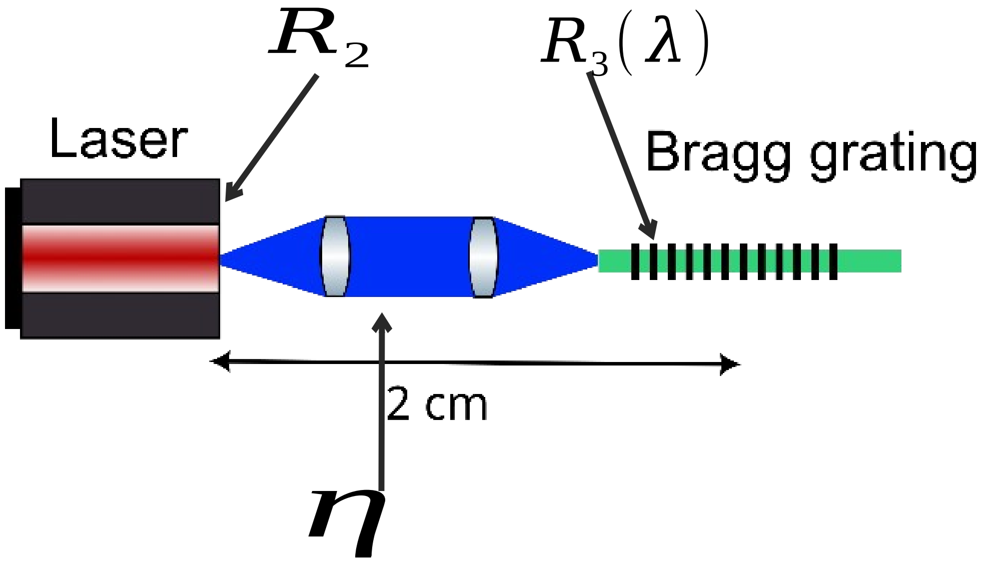
Single frequency linewidth: $\Delta\nu = \frac{\Delta\nu_0}{(1+C)^2}$

Feedback coefficient $C = \frac{\kappa\,\tau_{ex}}{\tau_{DL}}\sqrt{1+\alpha^2}$

$$\kappa_{ex} = (1-R_2)\times\frac{R_{2,eff}}{R_2}$$

$$R_{2,eff} = \eta^2 \times R_3$$

$$\tau_{CE} = \frac{2\,n_{CE}\,L_{CE}}{c}$$



Guidelines to optimize the linewidth narrowing :

> Minimizing output mirror reflectivity

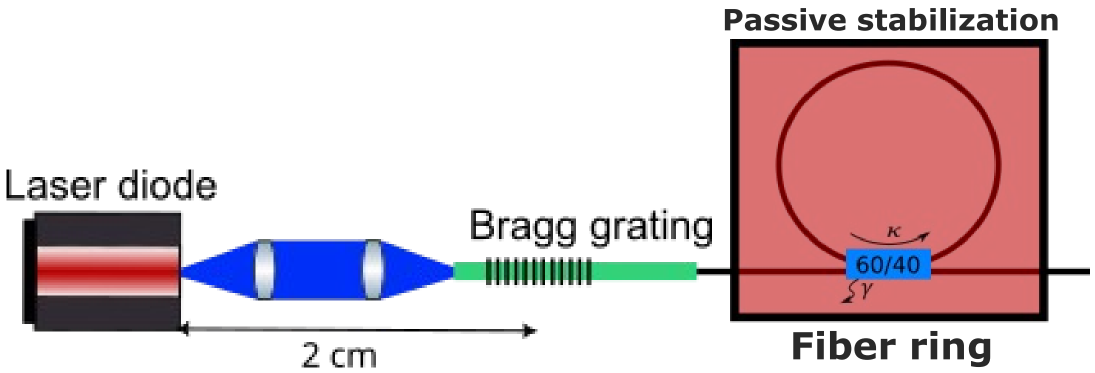
> Maximizing the Bragg reflectivity

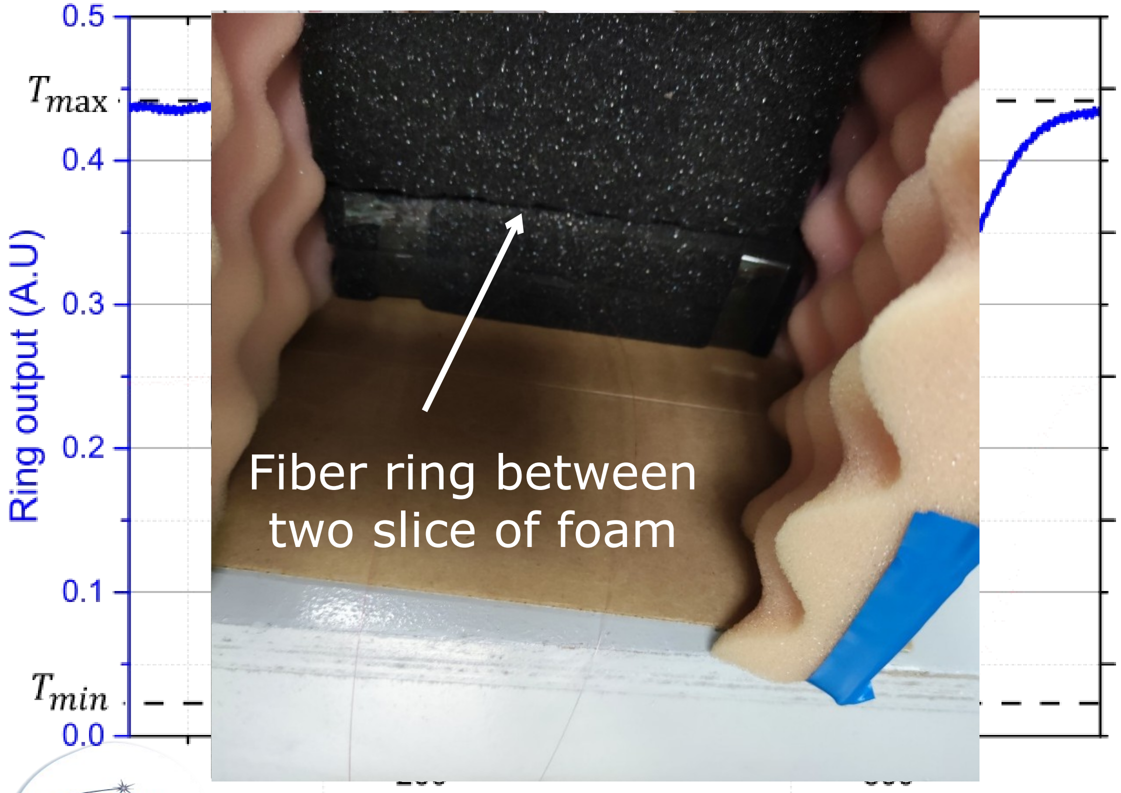
> Optimizing the coupling efficiency

> Optimizing the length of the external cavity

Petermann, K. *Laser Diode Modulation and Noise* (Springer Netherlands, 1998)

First frequency reference : a fiber ring resonator

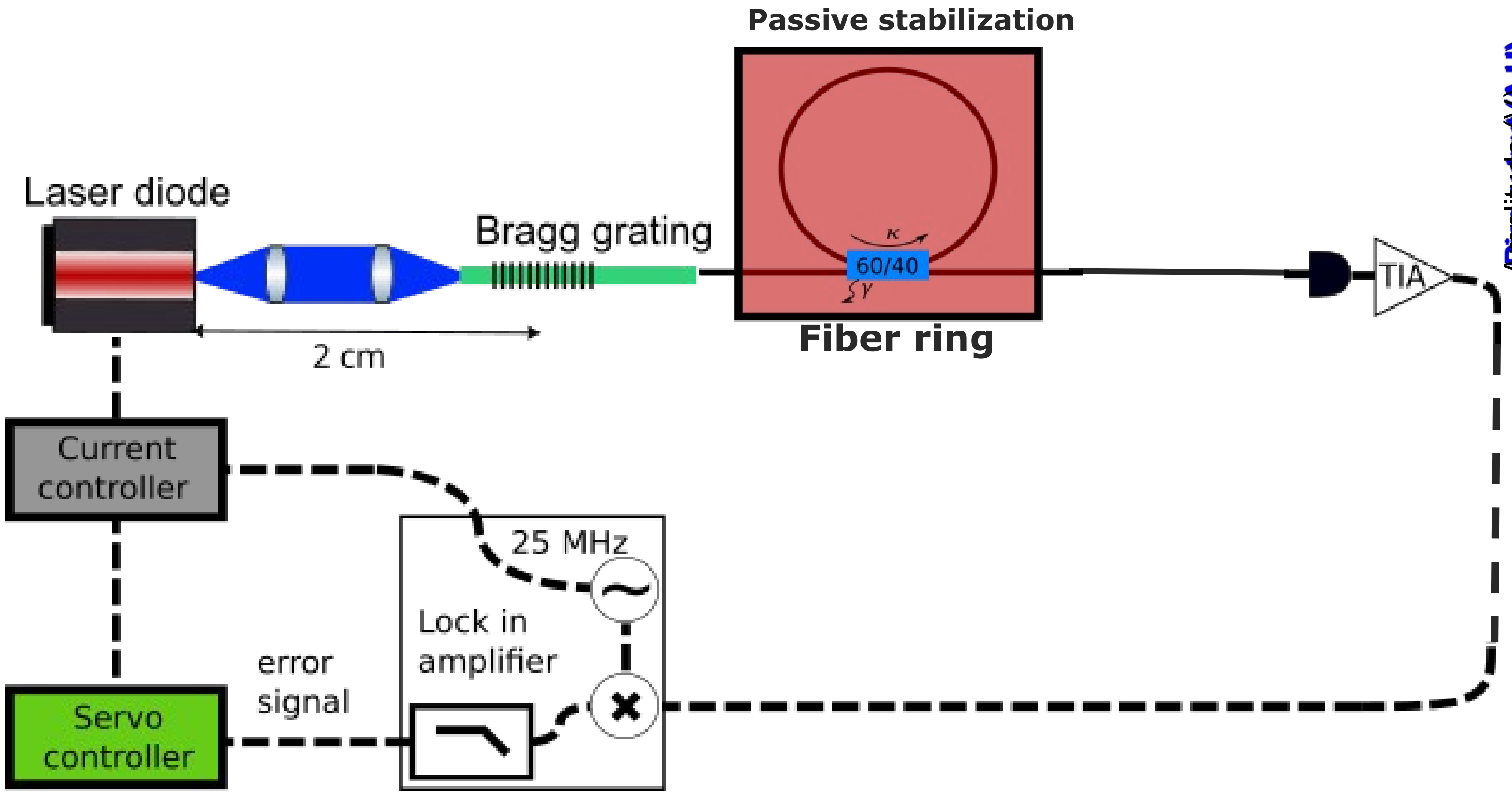


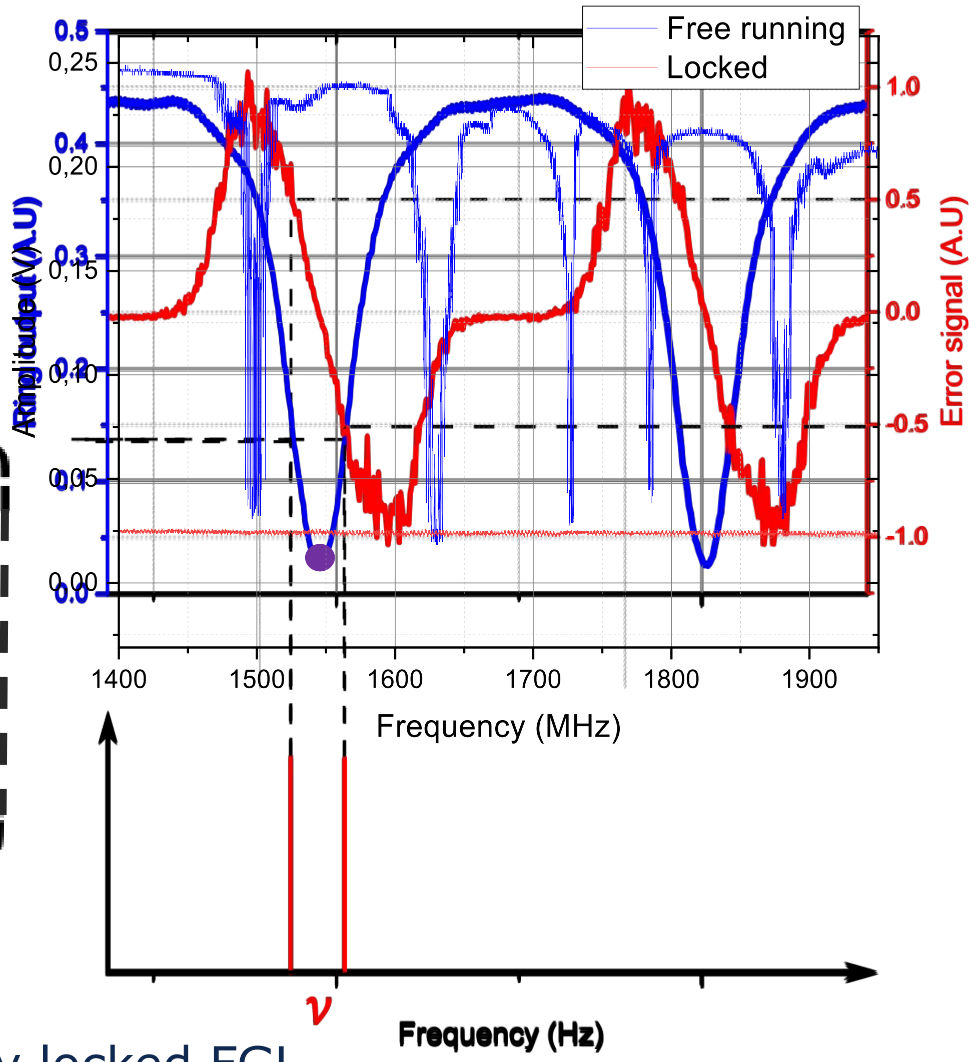


- ⇒ 2 m ring made by solding two of the outputs of a 60/40 coupler
- ⇒ Coupler insertion loss of 2.75 dB
- ⇒ Fiber loss > 30 dB/km
- ⇒ Isolation of the ring

Quality factor Q=

Frequency locking of the FGL on a fiber ring resonance





> Next step : frequency noise characterization of the frequency locked FGL