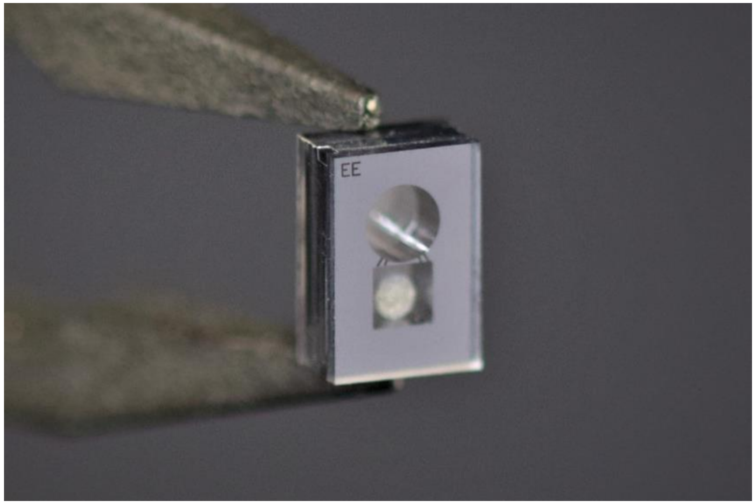
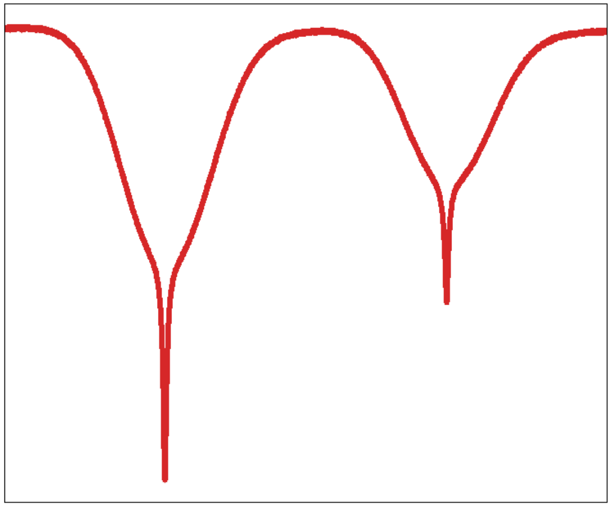
Cs-microcell stabilized-laser based on dual-frequency sub-Doppler spectroscopy





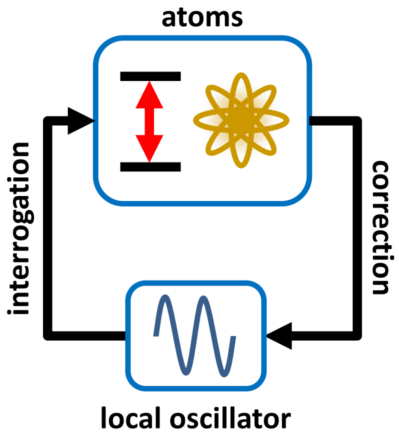
A. Gusching, J. Millo, I. Ryger, R. Vicarini, M. Abdel Hafiz, N. Passilly, and R. Boudot[1]

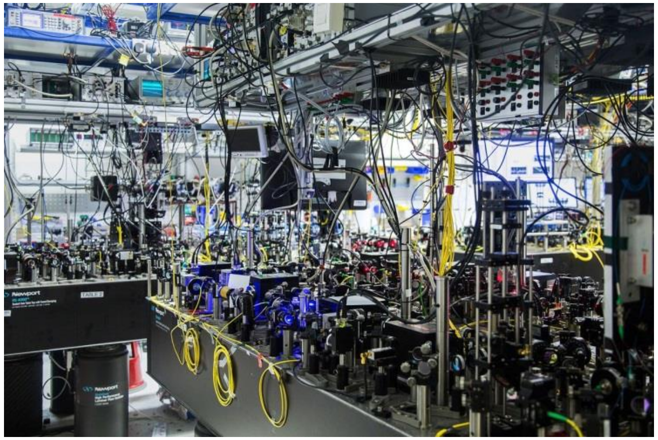
[1]*FEMTO-ST, CNRS, UBFC, Besançon, France*

Context

The second is the physical quantity measured with the most “precision”.

Best atomic clocks: fractional frequency stability levels in the 10^{-19} range



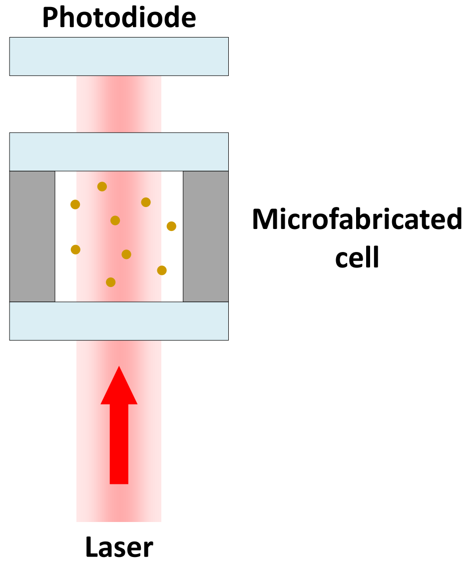


TAI
Fundamental physics

N. Huntemann and al., Phys. Rev. Lett. 116, 063001 (2016)
W. F. McGrew and al., Nature 564, 87-90 (2018)
E. Oelker and al., Nature Photonics 13, 714 (2019)
M. Takamoto and al., Nature Photonics 14, 411 (2020)

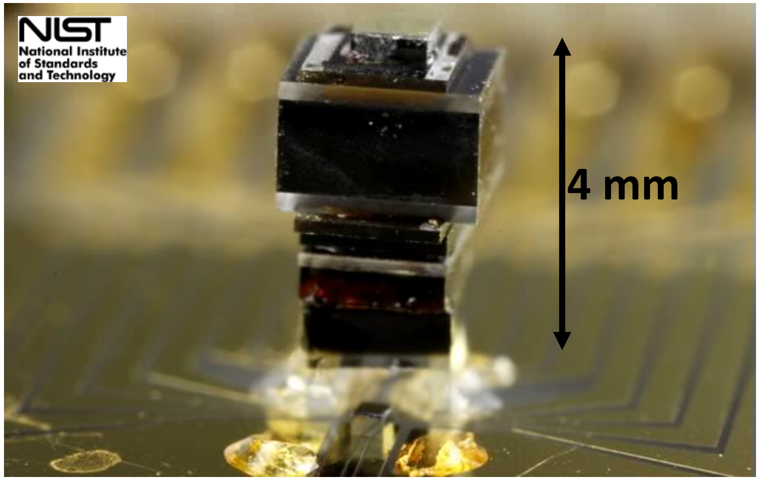
Miniaturized atomic clocks :

- Low SWaP budget
- Stability levels < 10^{-11} at 1 day

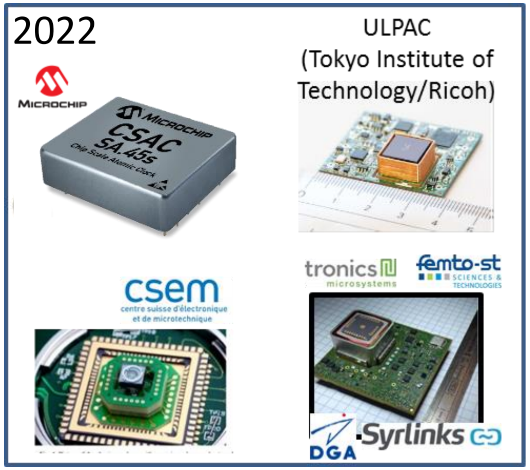


Atomic spectroscopy, MEMS technology, Photonics, Metrology
Applications: Navigation, Telecoms, Secure communications, etc.

CPT-based microwave chip-scale atomic clocks



S. Knappe et al., APL 85, 9, 1460 (2004)



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

Perfomances: 15 cm^3, 120 mW, 10^{-11} at 1 day (1 µs/day) [-40/+85°C]

100 times more stable than an OCXO at 1 day for a comparable volume-consumption ratio

Short-term stability

$$\sigma_y(\tau) \approx \frac{\Delta\nu}{\nu_0}\frac{1}{SNR}\tau^{-1/2}$$

Limitations / Drawbacks of CPT-based CSACs

Microwave clock transition (9.2 GHz)

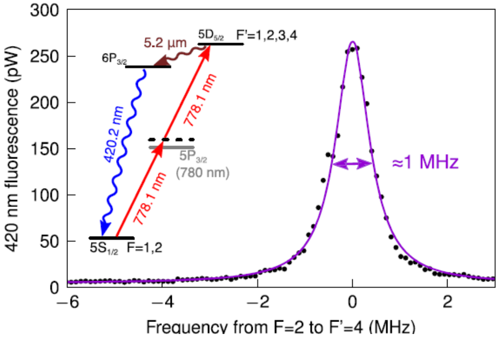
The FM noise of the VCSEL limits the short-term stability

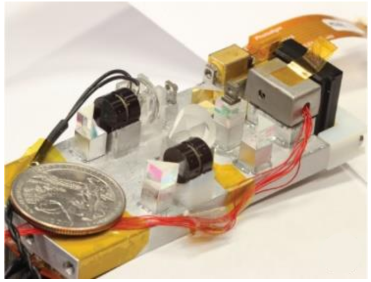
The presence of buffer gas in the cell jeopardizes the long-term stability and accuracy

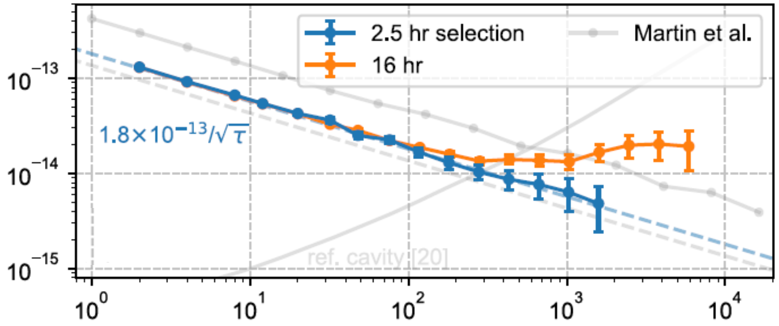
Interrogation of optical transitions in MEMS cells using sub-Doppler spectroscopy techniques
(« simple », no UHV, no laser cooling)

Compact cell-based optical references

Two-photon transition (778 nm) in Rb MEMS cell

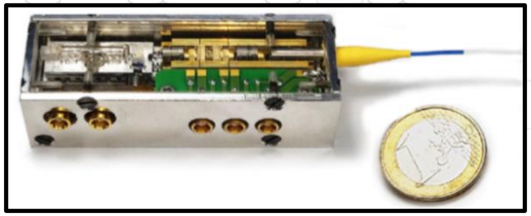


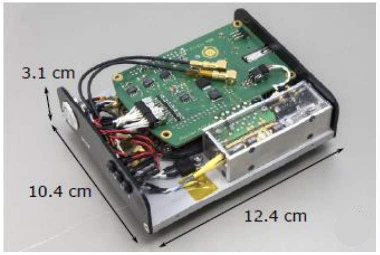


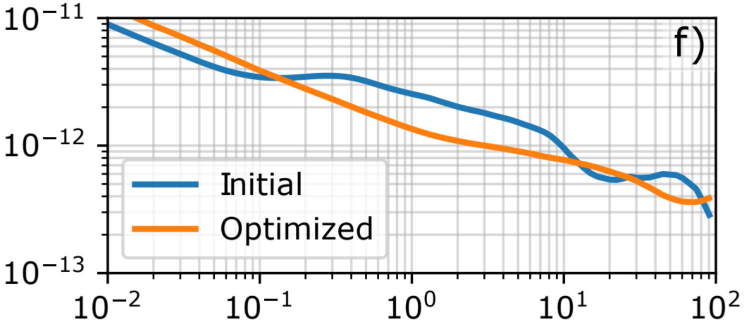


DBR : 2.8 10^{-12} @ 1 s
ECDL : 1.8 10^{-13} @ 1s

Saturated absorption in glass-blown Rb cell





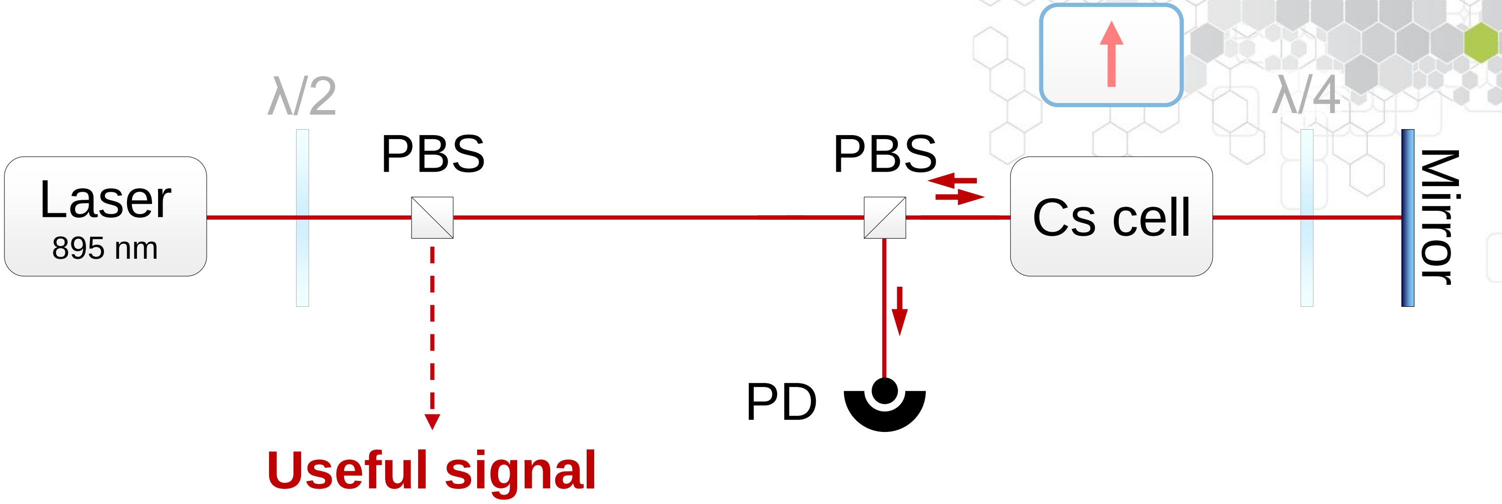


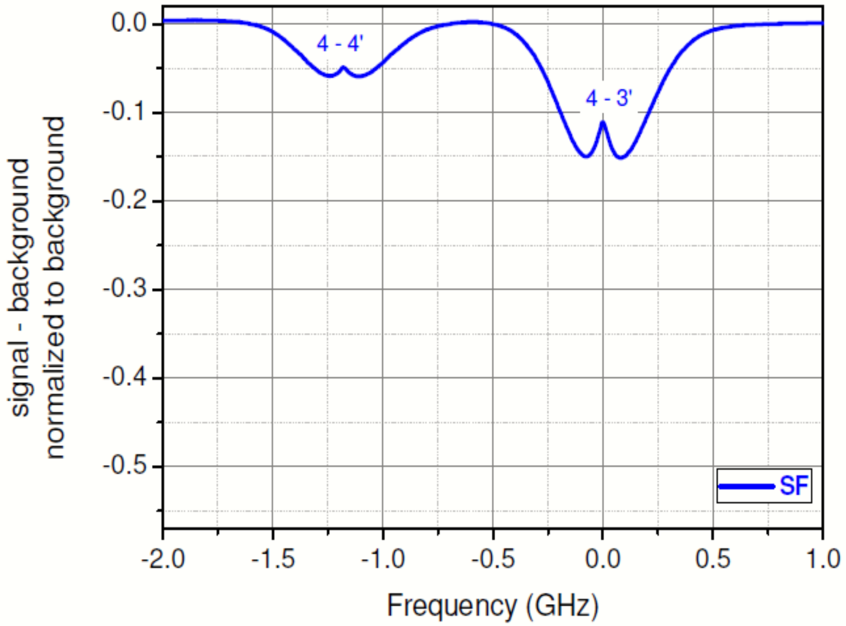
1.4 10^{-12} @ 1 s

Z. Newman et al., Optica 6, 5, 680 (2018)
V. Maurice et al., Opt. Exp. 28, 17 (2020)
Z. Newman et al., Opt. Lett. 46, 18, 4702 (2021)

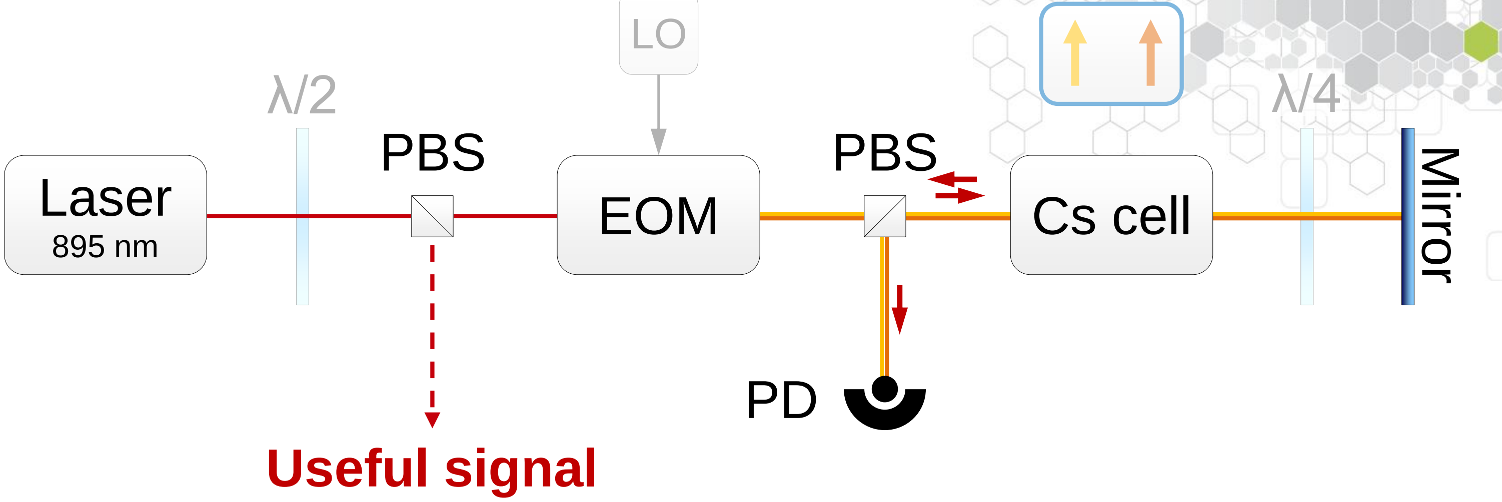
A. Strangfeld et al. Opt. Exp. 30, 7, 12039 (2022)

Sub-Doppler spectroscopy





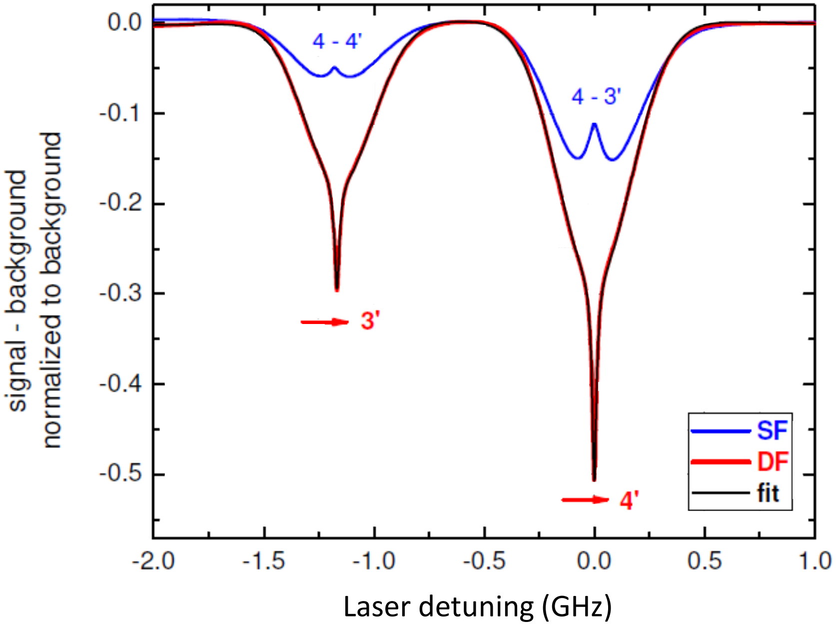
Dual-frequency sub-Doppler spectroscopy (DFSDS)



Null magnetic field
Orthogonally polarized counter-propagating beams

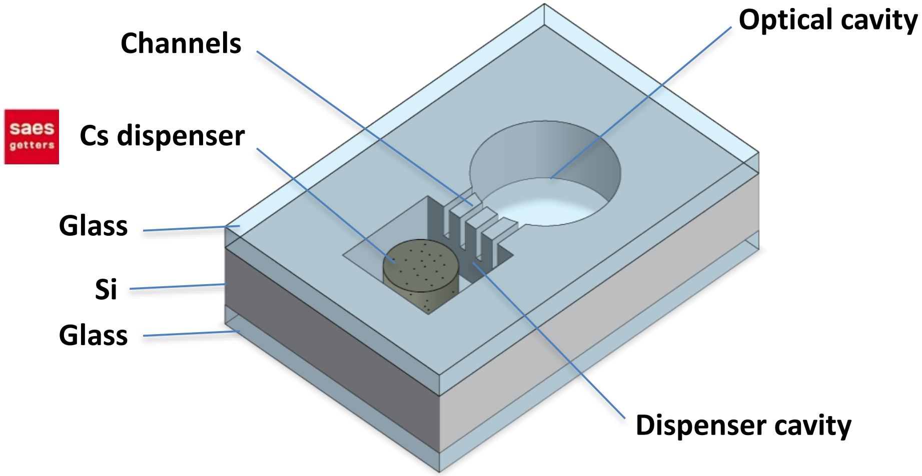
Contribution of Zeeman and hyperfine dark states
+ optical pumping effects.

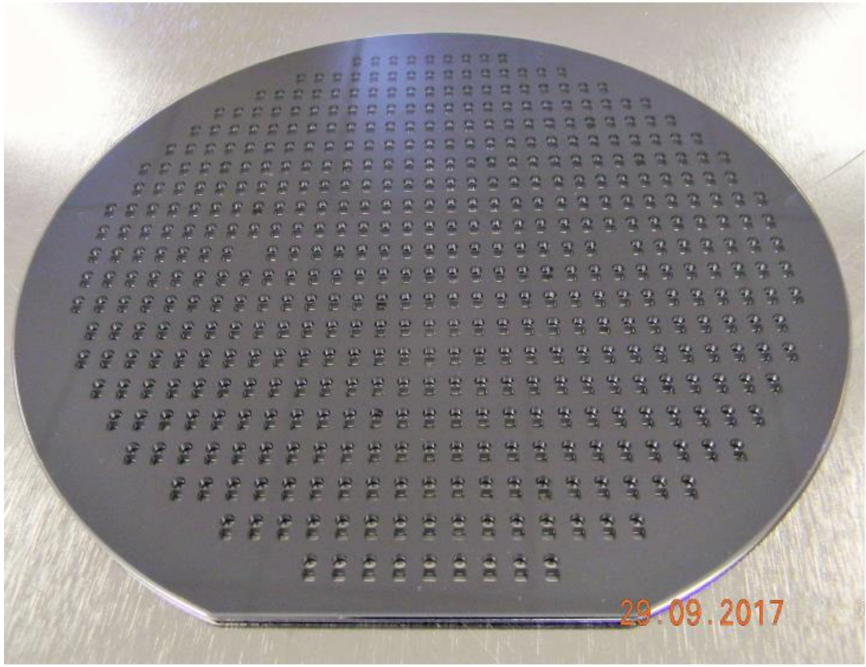
Dual-frequency sub-Doppler spectroscopy
high-contrast sign-reversed absorption spikes



M. Abdel Hafiz et al., Opt. Lett. 41, 13, 2982 (2016).
M. Abdel Hafiz et al., New J. Phys. 19, 073028 (2017).
D. Brazhnikov, Phys. Rev. A 99, 062508 (2019).

MEMS cell technology





Wafer at Tronics - TDK

- Glass-silicon-glass assembly
- Processes: DRIE and anodic bonding
- **No buffer gas**

Post-sealing Cs filling by laser activation of a cesium dispenser

Simple and effective method for a well-controlled cell atmosphere

⇩

Industrially transferred

J. Kitching et al., Appl. Phys. Lett. 81, 3, 553 (2002)
A. Douahi et al., Elec. Lett. 43, 5, 34 (2007)

M. Hasegawa et al., Sensors Actuators 167, 2, 594 (2011)
R. Vicarini et al., Sensors Actuators 280, 99 (2018)

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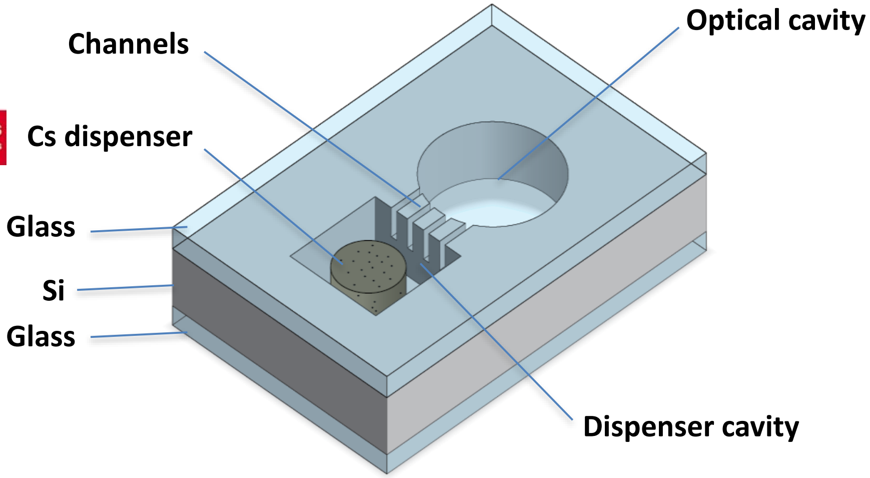

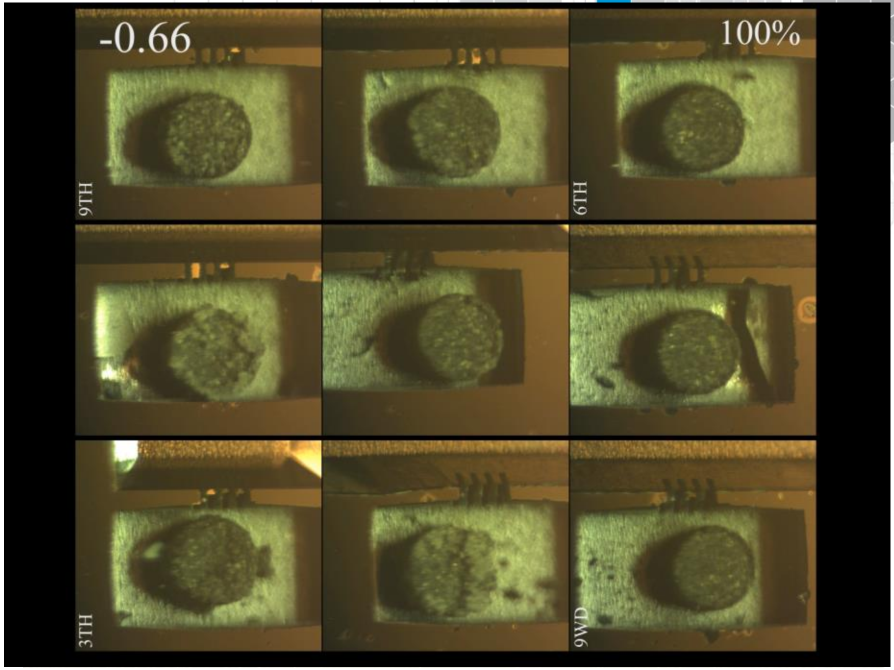

From V. Maurice PhD thesis

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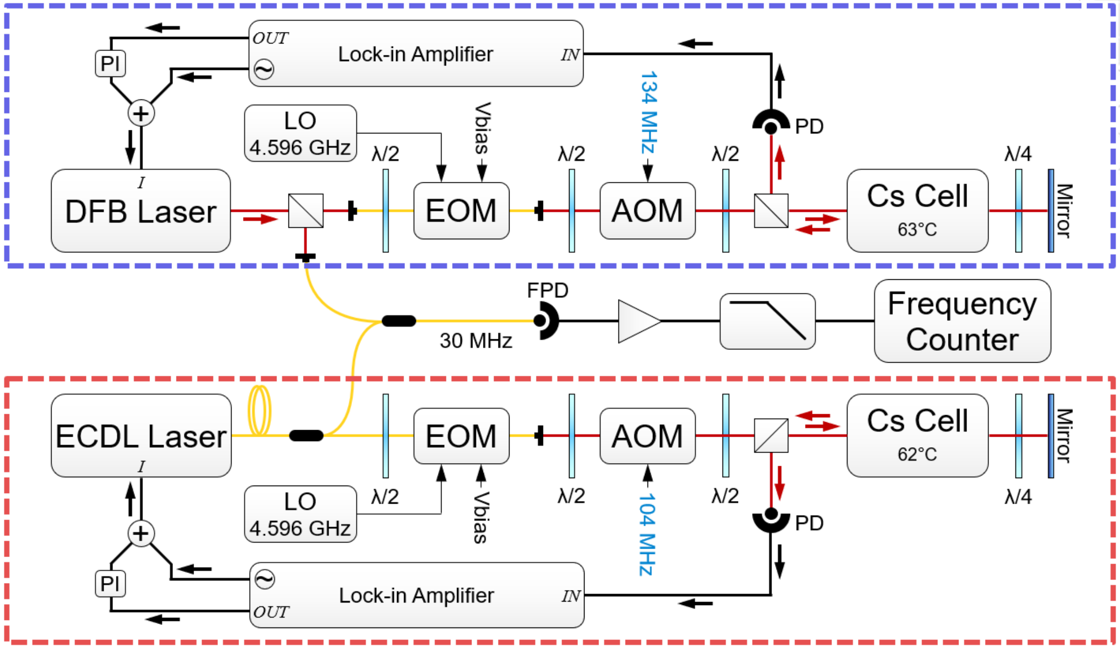
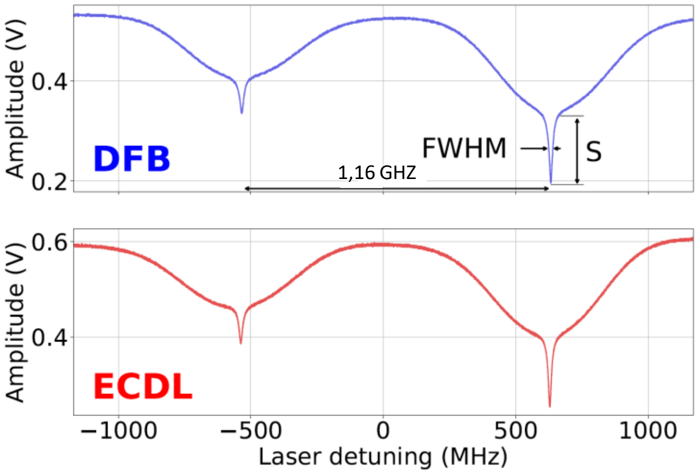
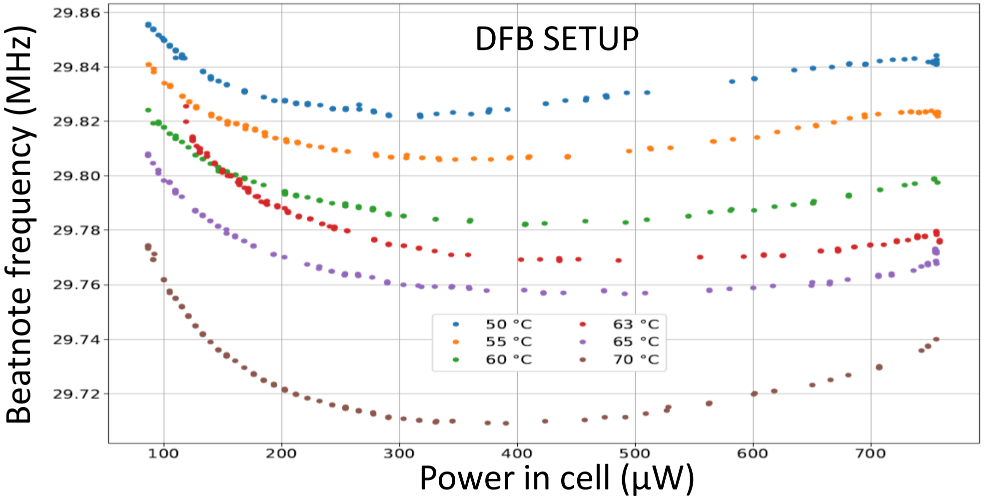
Beatnote setup (ECDL Vs DFB)

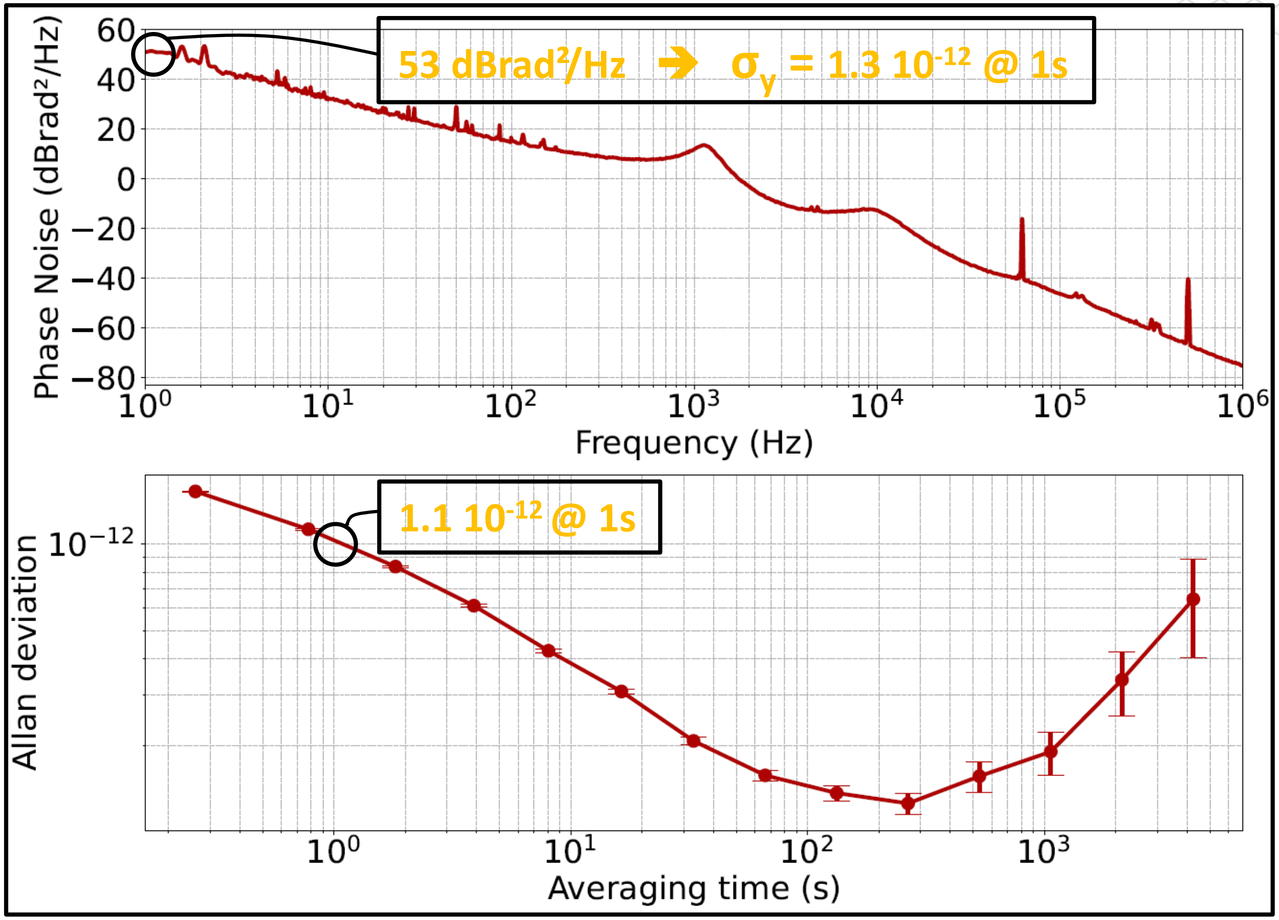


A. Gusching et al., J. Opt. Soc. Am. B 38, 11, 3254 (2021)





Phase noise and stability of the beatnote (ECDL Vs DFB)



53 dBrad²/Hz ➔ σ_y = 1.3 10^{-12} @ 1s

1.1 10^{-12} @ 1s

A. Gusching et al., J. Opt. Soc. Am. B 38, 11, 3254 (2021)

Noise budget

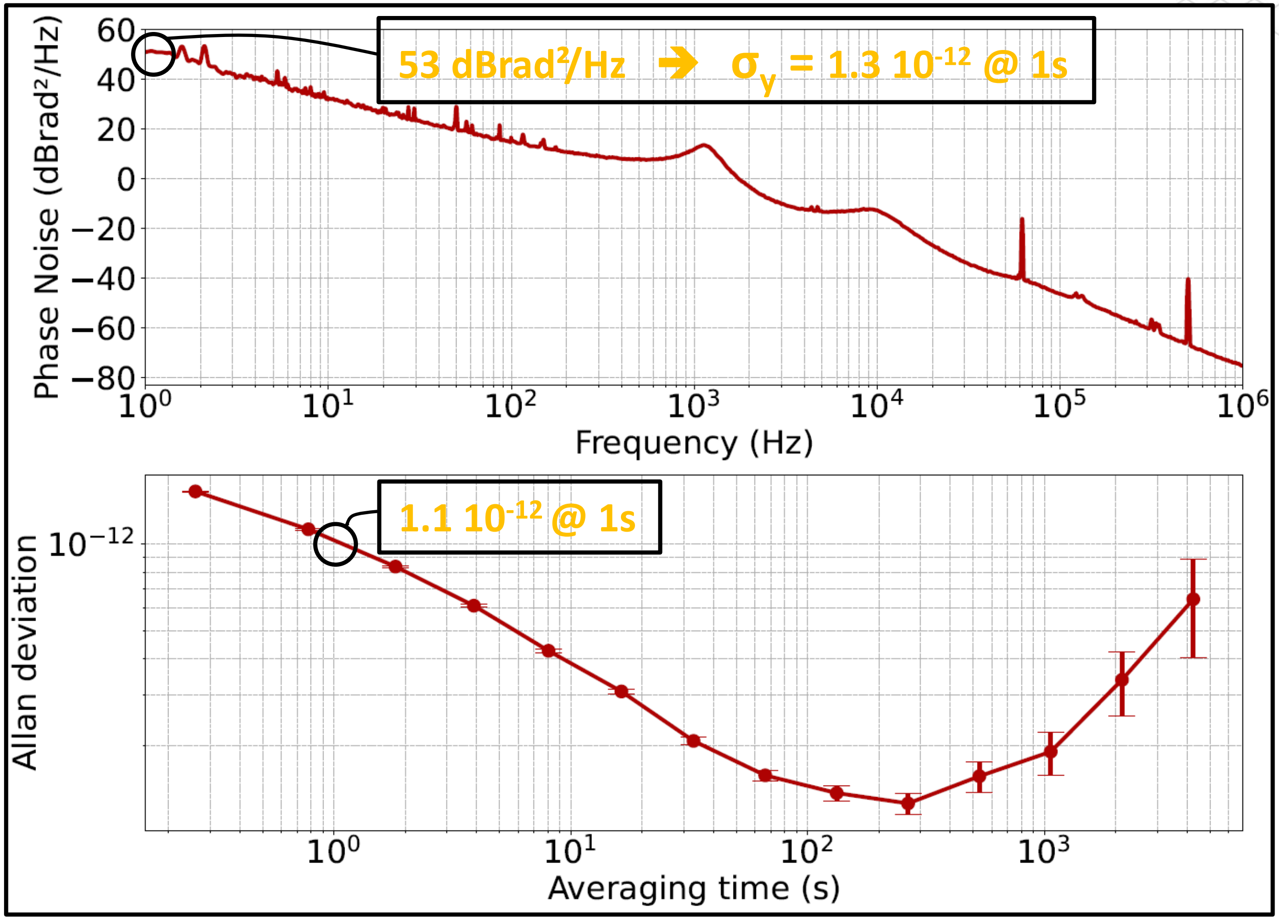
Properties	DFB	ECDL
S (mV)	126	139
FWHM (MHz)	14.7	14.2
S_l (V/Hz)	8.6×10^{-9}	9.8×10^{-9}
C	0.65	0.55
Absorption (%)	63.1	58.6
P_i (μW)	450	450
P_o (μW)	166	186.5
f_M (kHz)	500	61.95
Noise source	DFB	ECDL
σ_{sn} (1 s)	3.5×10^{-15}	3.8×10^{-15}
σ_{pd} (1 s)	3.9×10^{-14}	6×10^{-14}
σ_{AM-AM} (1 s)	3.8×10^{-14}	3.0×10^{-13}
σ_{FM-AM} (1 s)	4.4×10^{-13}	4.3×10^{-13}
σ_{LO} (1 s)	1.5×10^{-12}	5.75×10^{-13}
σ_y (1 s)	1.55×10^{-12}	7.8×10^{-13}

Predicted short-term stability ≈ **10^{-12} at 1 s**

Limitation : Intermodulation effect due to the DFB laser FM noise

Need an ultra-stable 895 nm reference to measure the microcell-ECDL

Phase noise and stability of the beatnote (ECDL Vs DFB)



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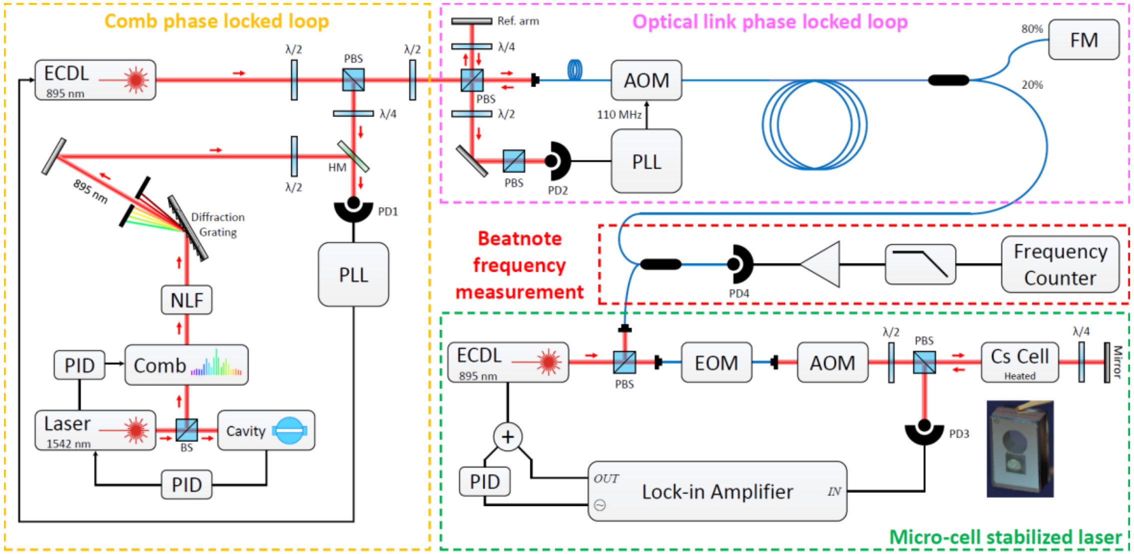
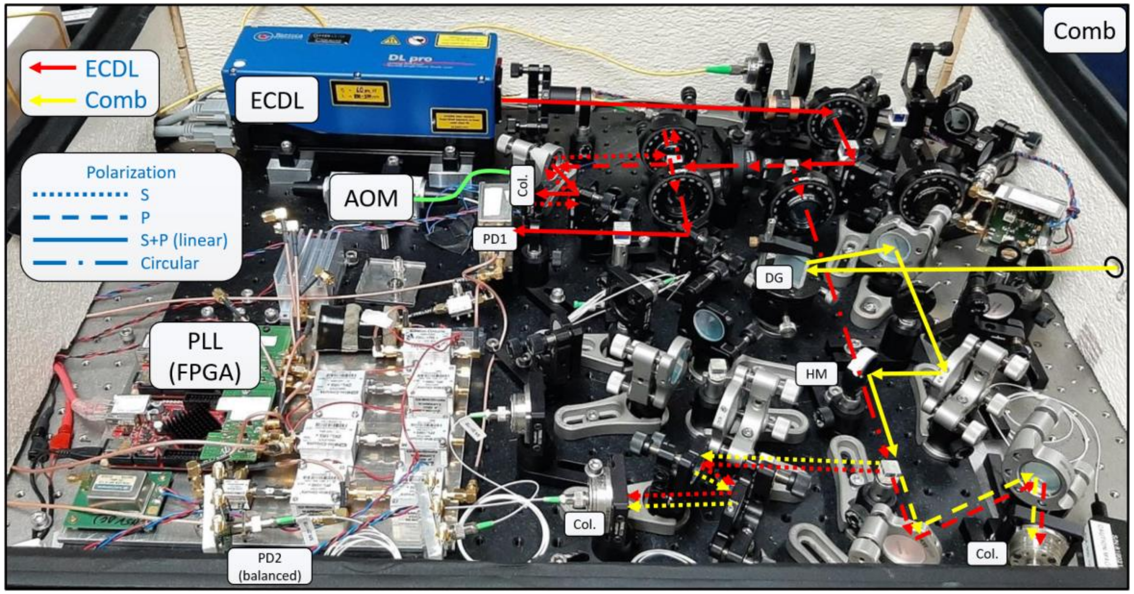
Cavity-stabilized 895 nm reference



Laser on ultra-stable cavity : 2.10^{-15} at 1 s



1542 nm laser locked on ultra-stable ULE cavity

Comb (Menlo) locked on cavity-Laser

Doubling and spanning of the Comb with NLF

Phase-lock of a local ECDL on a comb tooth at 895 nm

Transfer of the ECDL to the microcell-ECDL lab through a compensated fiber link

Beatnote between comb-locked ECDL and microcell-ECDL

Conclusions and “short-term” perspectives

Stability of microcell-stabilized lasers using DFSDS (DFB Vs ECDL)
Allan deviation ≈ **$1x10^{-12}$** at 1s (in good agreement with phase noise)
Limited by the DFB laser FM noise

Development of a cavity-stabilize reference at 895 nm
using a frequency comb and an ECDL laser

Studies in progress to understand stability limitations after 100 s

↓

Pursue sensitivity measurements (cell temperature, microwaves, B-field, etc.)
Mitigate the cavity-stabilized laser contribution
Compact design