Single-frequency diode-pumped semiconductor laser tuned on a Cs transition

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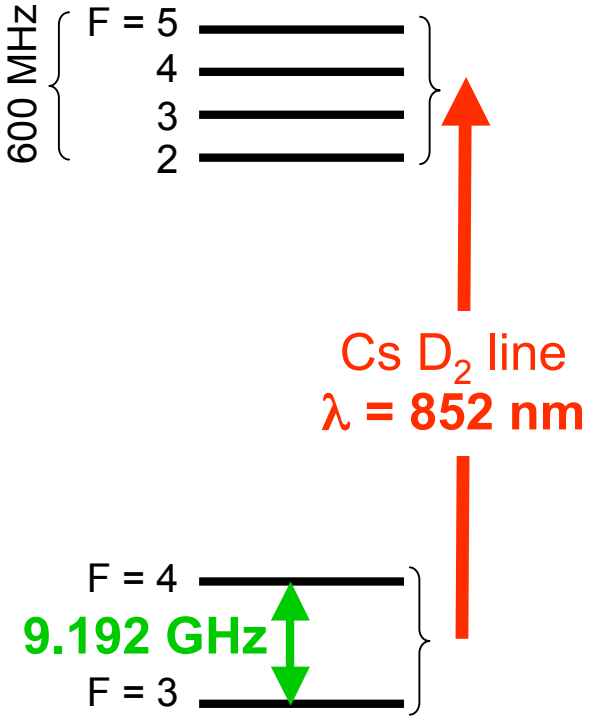
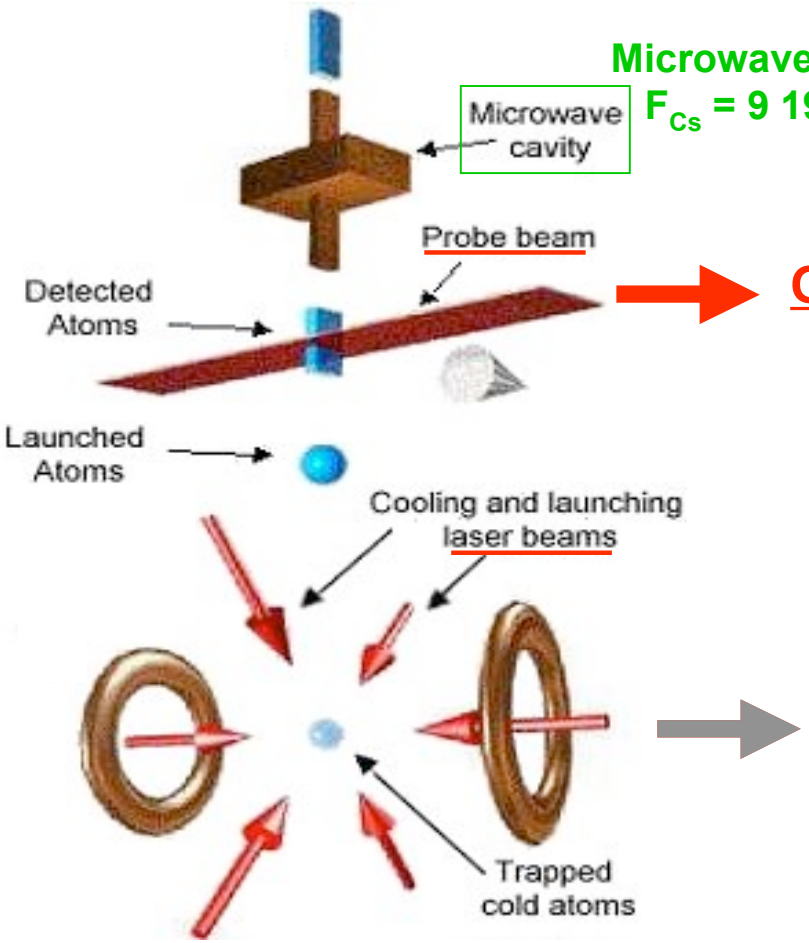
Lasers in Cesium atomic clocks



Cs atomic levels



Scheme of an atomic fountain

Microwave interrogation :
F_{Cs} = 9 192 631 770 Hz

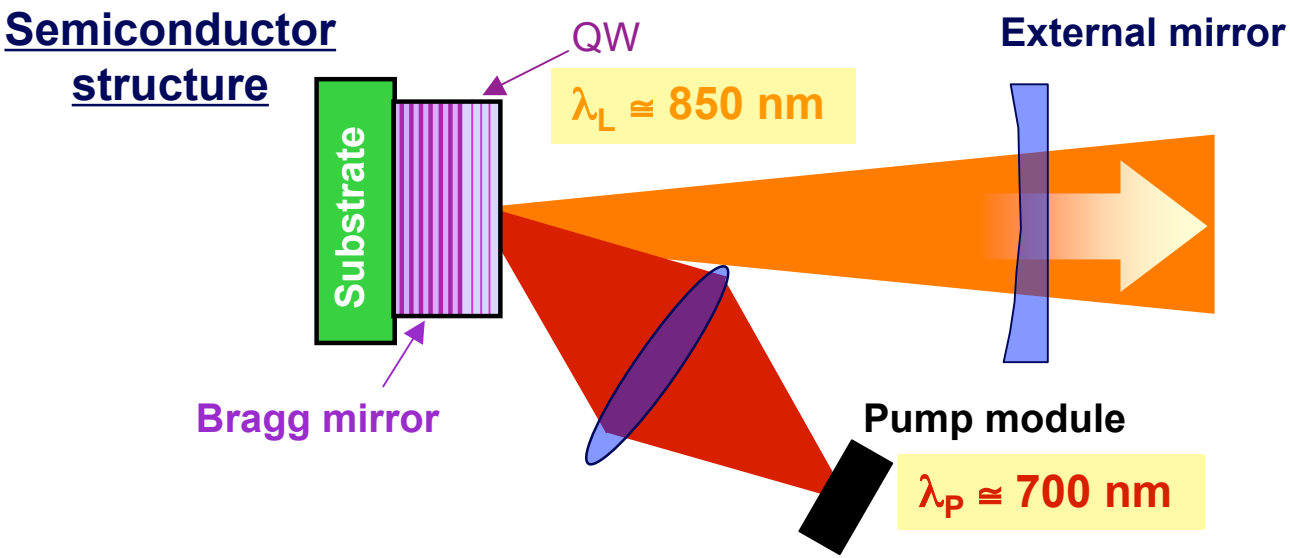
Optical Detection
$\Delta\nu$ << 5 MHz
Extended-cavity laser diodes

Atom cooling
P_{opt} > 200 mW
DFB/DBR diodes, MOPA, …

Need for **high-power** and **narrow-linewidth** sources emitting at the Cesium D_2 line (852 nm)

⇒ *a single OP-VECSEL ?*

OP-VECSEL at 850 nm



- **High power** in Optically Pumped-VECSEL

  30 W @ 980 nm, $M^2 = 3$ (Coherent - Photonics West '04)

  1.0 W in-well pump / 0.7 W @ 850 nm, $M^2 = 5$ (University of Strathclyde)

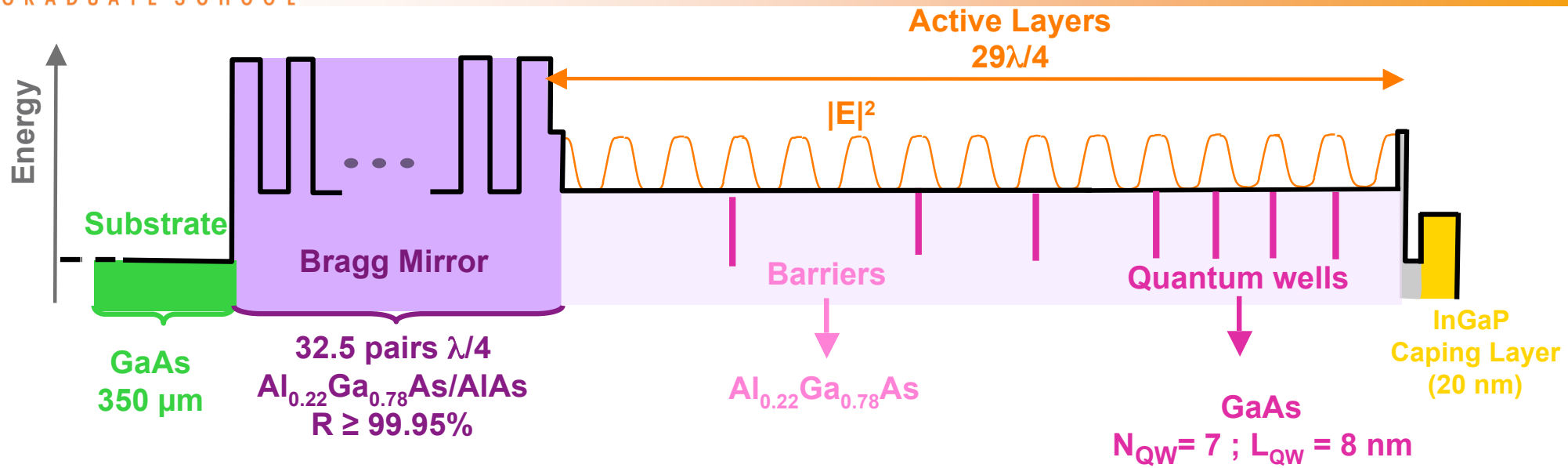
- No spatial hole-burning : **single-frequency** in simple linear cavity

  500 mW @ 1003 nm (Jacquemet et al, App.Phys. B 86, 503 (2007))

  42 mW @ 870 nm, $\Delta\nu_L \cong 3$ kHz (Holm et al, IEEE PTL 11, 1551 (1999))

- Linearly polarized, circular TEM_{00} beam

Design of the semiconductor structure



- λ_L = 852 nm
- Barriers absorption at $\lambda_P \leq 720$ nm

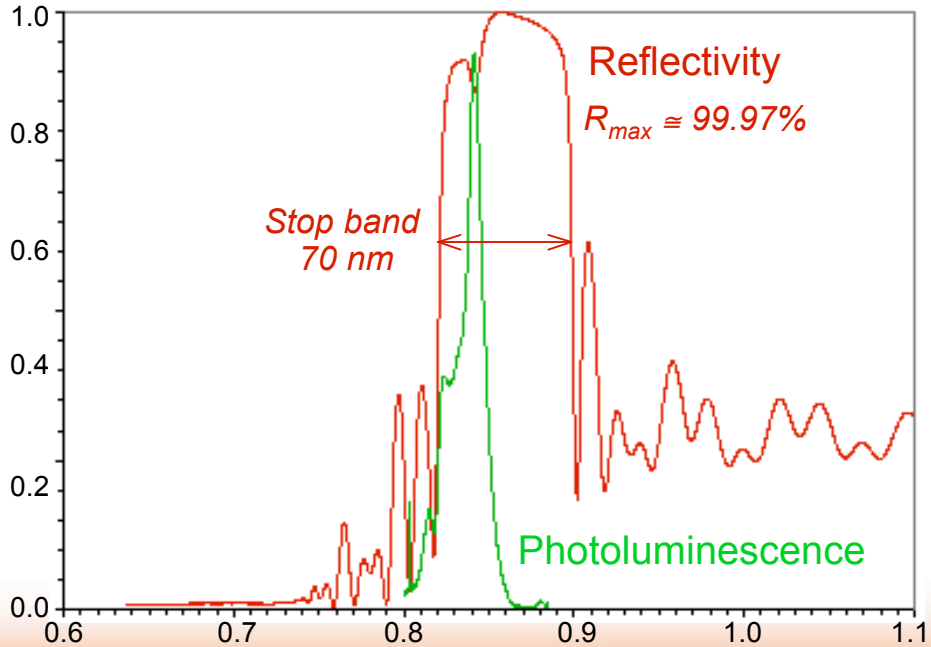
  $e_b \cong 2\ \mu m \Rightarrow \eta_P = 85\%$

- AR coating (Si_3N_4) at air/SC surface for :

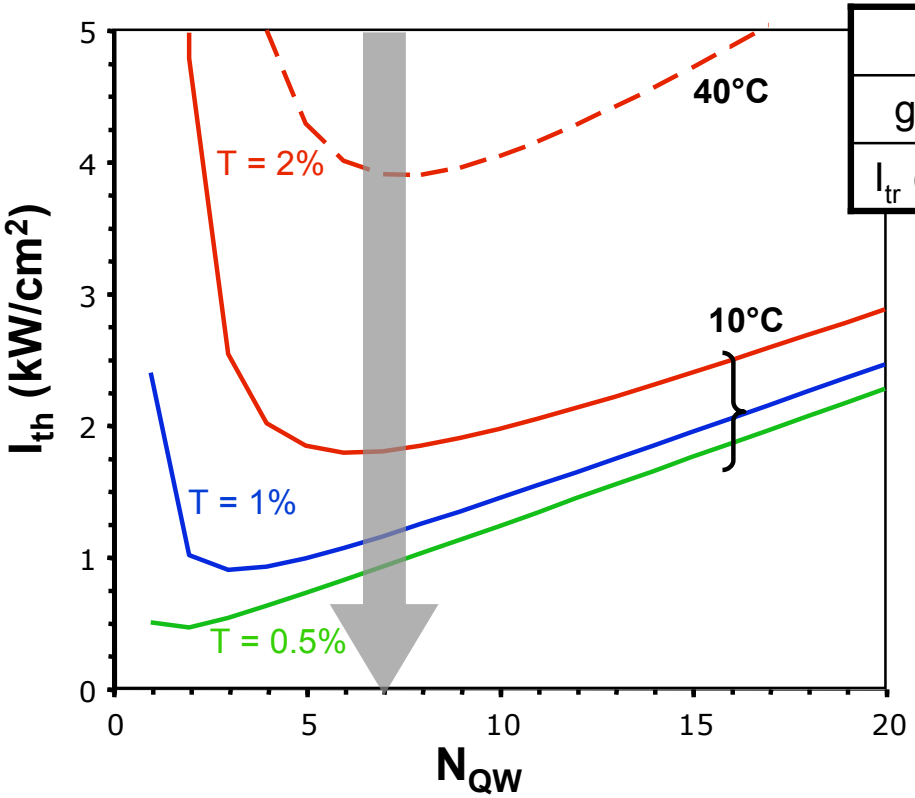
  maximum pump transmission

  + reduction of microcavity etalon effect

- Structure grown by MOCVD



Design optimization



T(°C)	10°C	40°C
g_0(cm^{-1})	1000	830
I_{tr} (W/cm²)	105	190

Experimental parameters

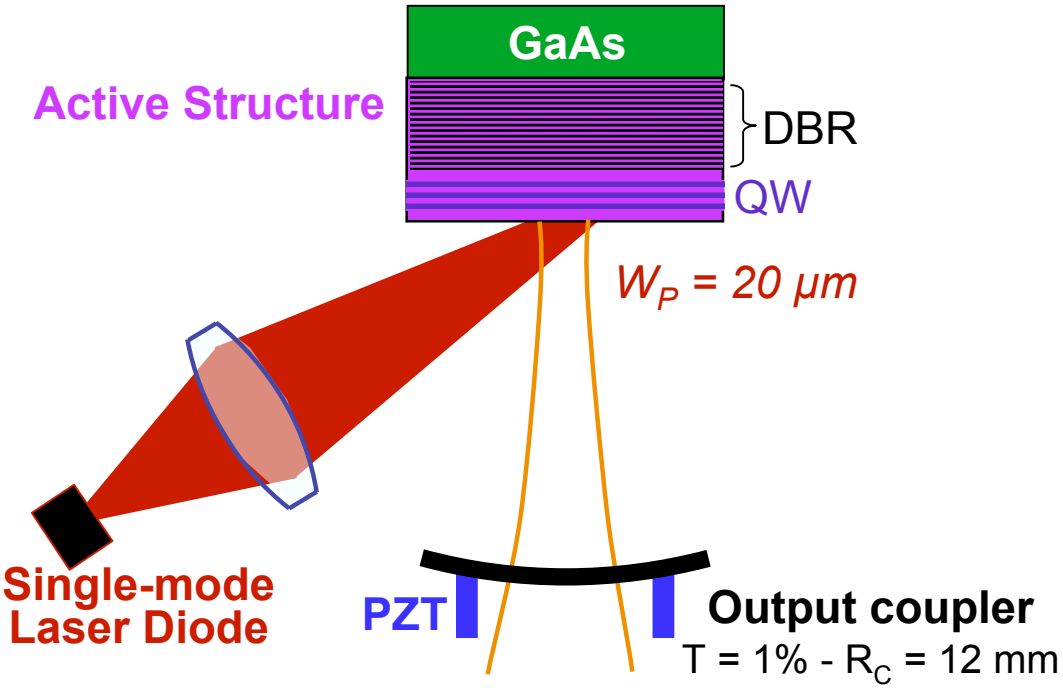
Threshold intensity

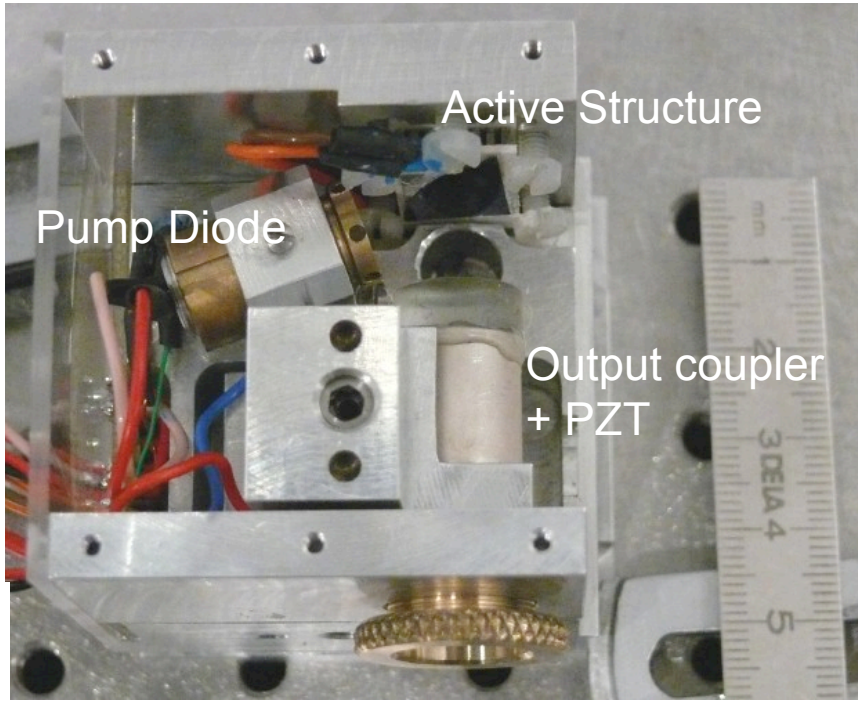
$$I_{th} = N_{QW} I_{tr} \times \exp\left(\frac{T}{2\Gamma N_{QW} L_{QW} g_0}\right)$$

- Low threshold pump intensity I_{th} for high opt-opt efficiency

⇒ N_{QW}= 7 is optimal for ~ 2% losses

Single-frequency setup

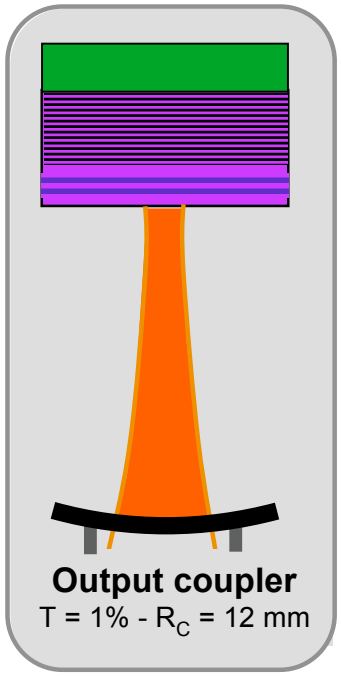


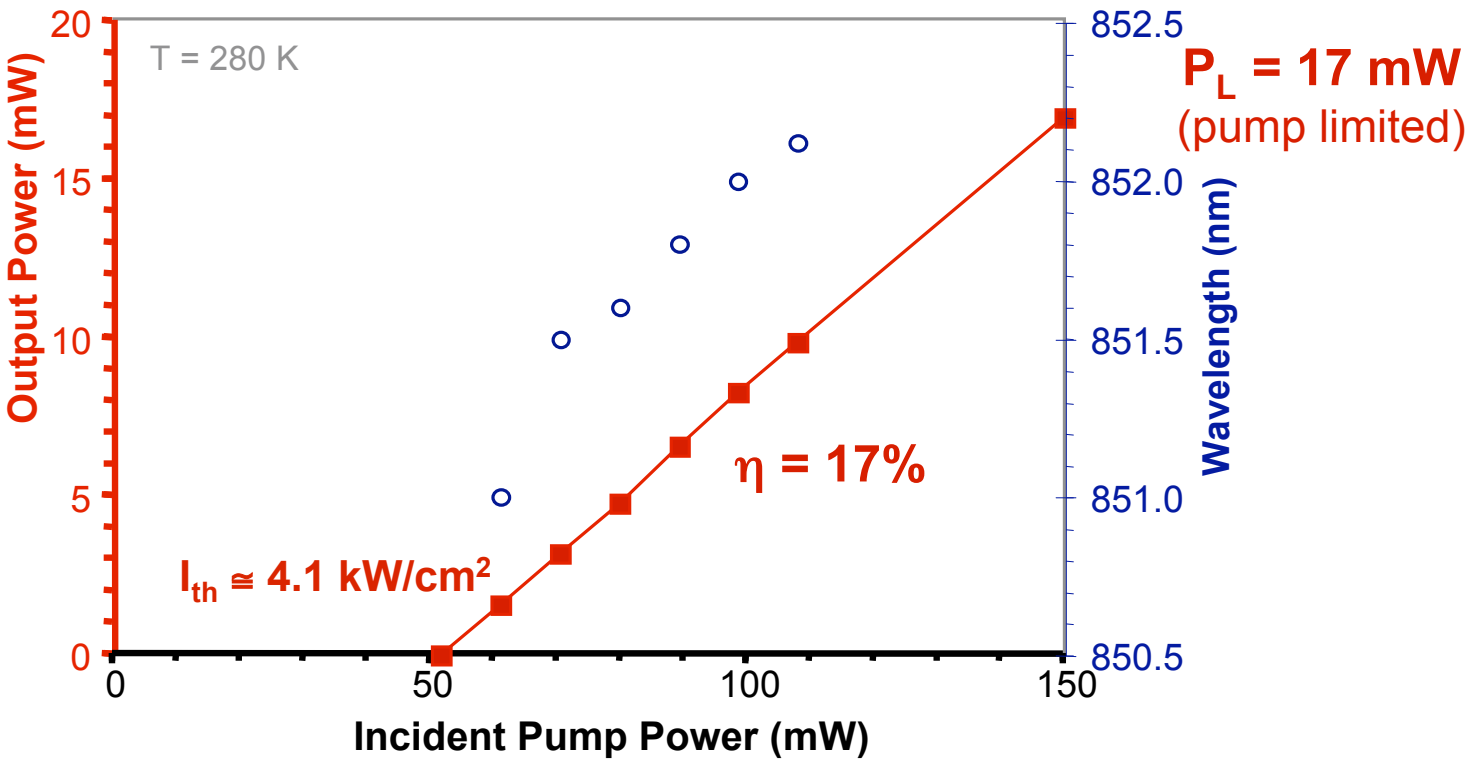


- Compact plane-concave cavity : $L_{ext} \cong 10$ mm
- Single-transverse mode pump laser diode :

  P_{max}= 120 mW (245 mA) at λ_P = 658 nm
- 52 x 52 x 58 mm^3 integrated setup for improved mechanical stability

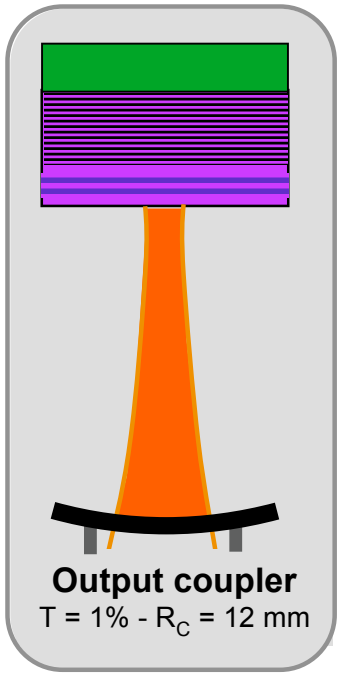
Single-frequency emission

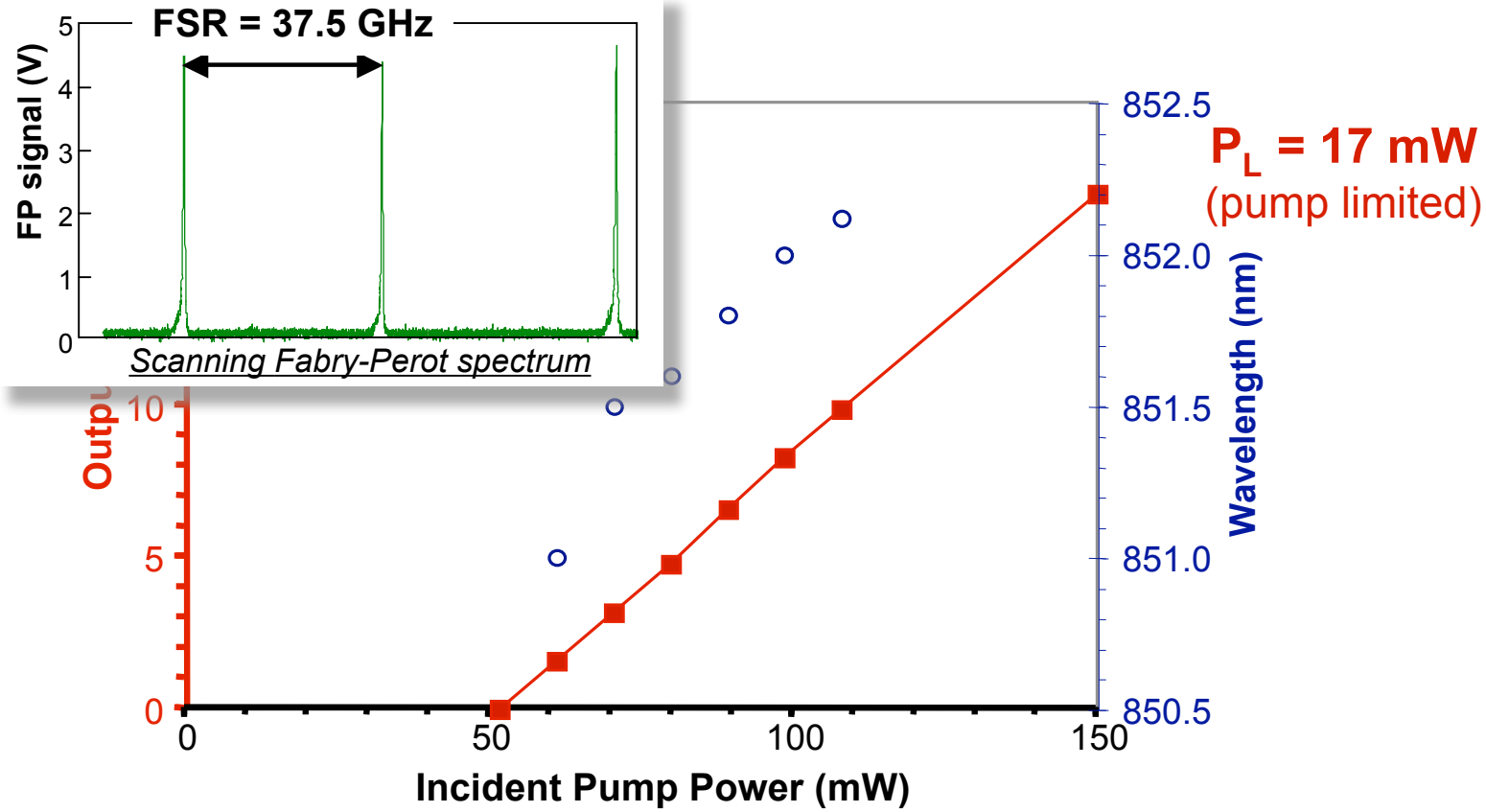




- Low threshold: 4.1 kW/cm²
- Good beam quality : M² < 1.2 and linear polarization

Single-frequency emission





- Single frequency operation **without intracavity λ-selective element** :

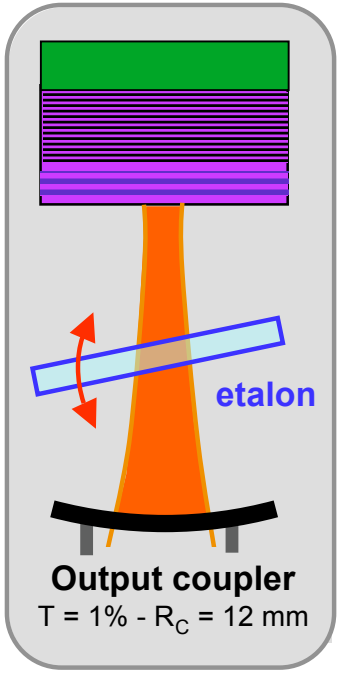
  checked with a high Finesse (F = 130) 37.5-GHz-FSR scanning Fabry-Perot

  SMSR > 25 dB

Single-mode spectrum in $t_{SM} \cong T_C\left(\frac{\Gamma}{FSR}\right)^2 \cong 1\text{ms}$ for L_{ext} = 10 mm $\begin{cases} T_C = \text{photon lifetime (~ 10 ns)} \\ \Gamma = \text{gain bandwidth (~ 10 nm)} \end{cases}$

Jacquemet et al, App.Phys. B (2006)

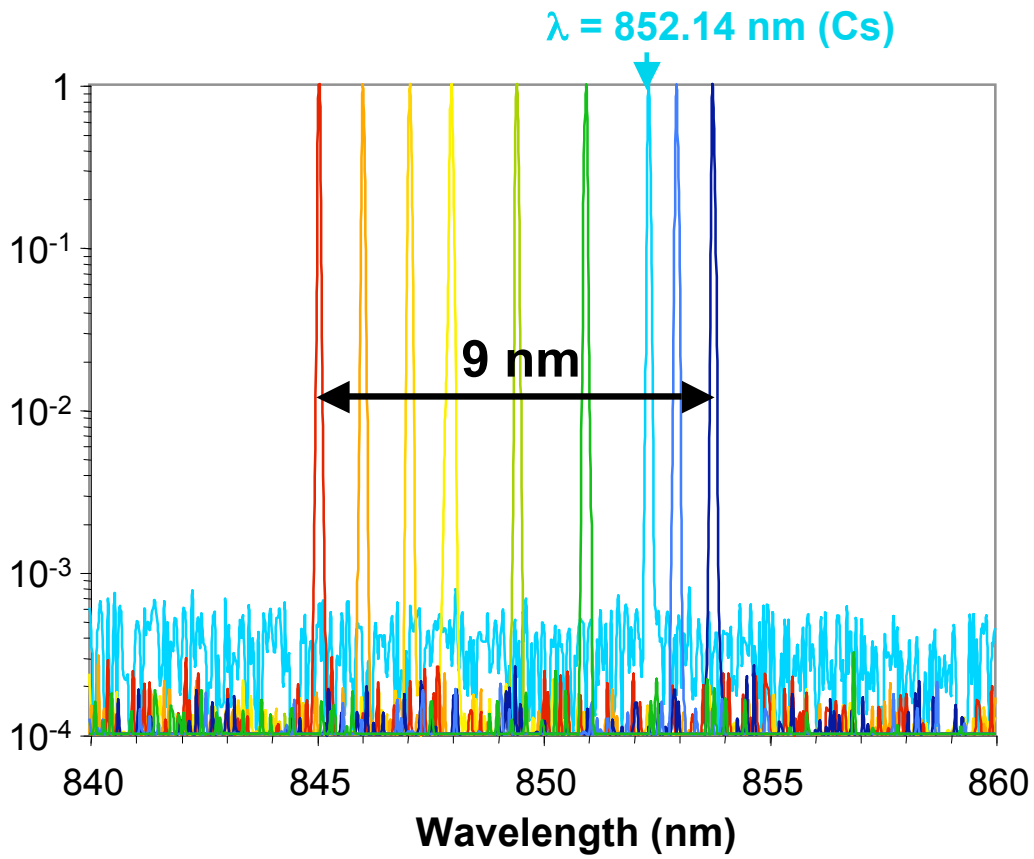
With an intracavity etalon



25-µm thick (≅ 9 nm FSR) silica etalon

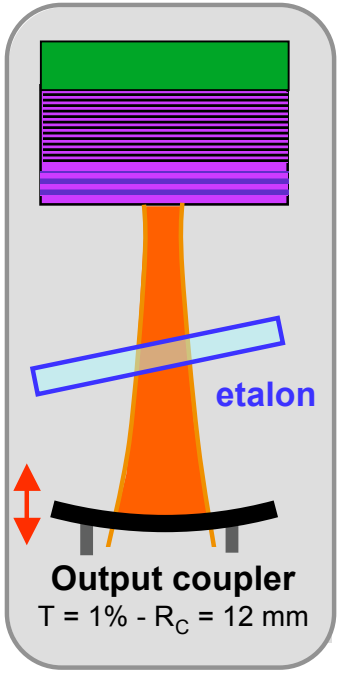
⇒ λ independent of operating conditions (T°, P_P)

\+ improved long-term stability

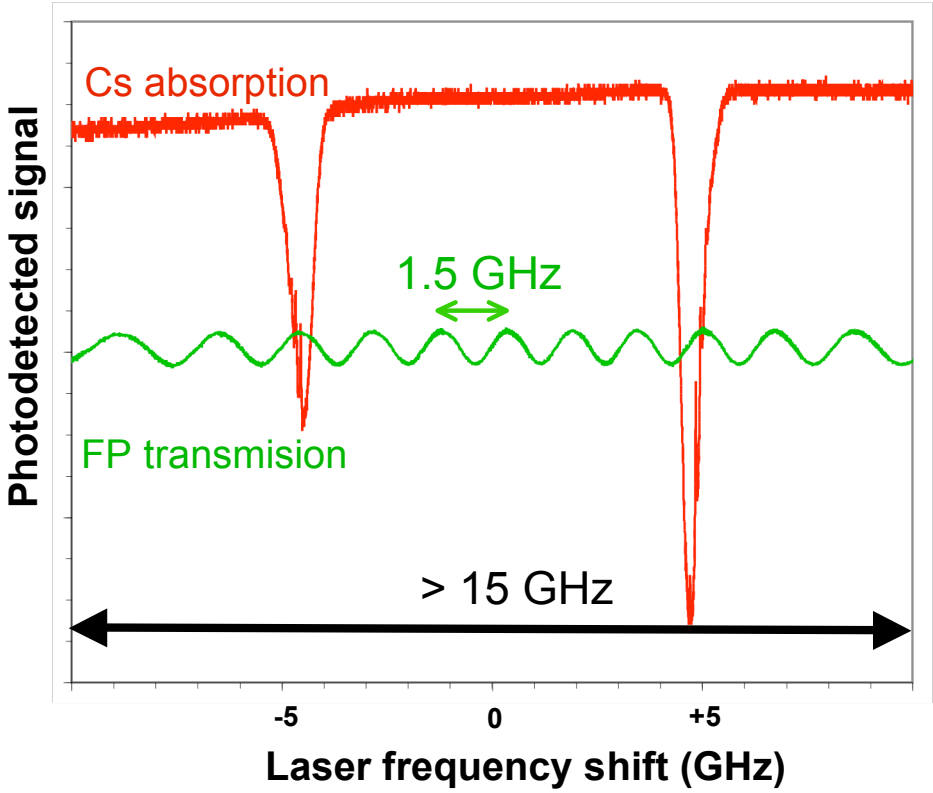


- Increased losses at θ ≠ 0° ⇒ ↘ laser power : P_L = 7 mW @ 852.14 nm

Single-frequency tunability



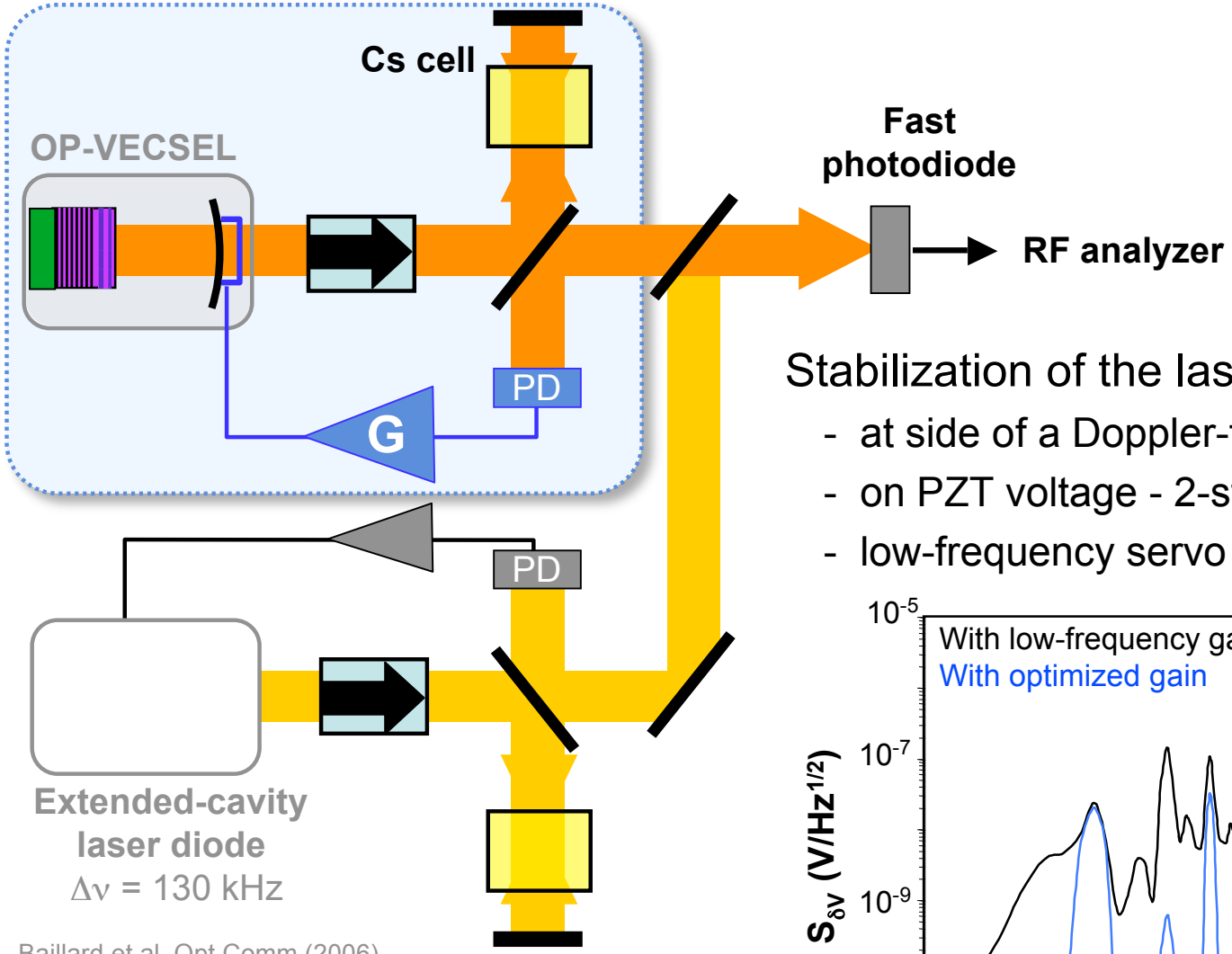
- more than 15 GHz continuous tunability (without mode-hops) by translating the external cavity mirror with PZT



Frequency-shift measurement with a low-finesse static 1.5-GHz-FSR Fabry-Perot

⇒ Tuning over the Cs-absorption spectrum (9 GHz)

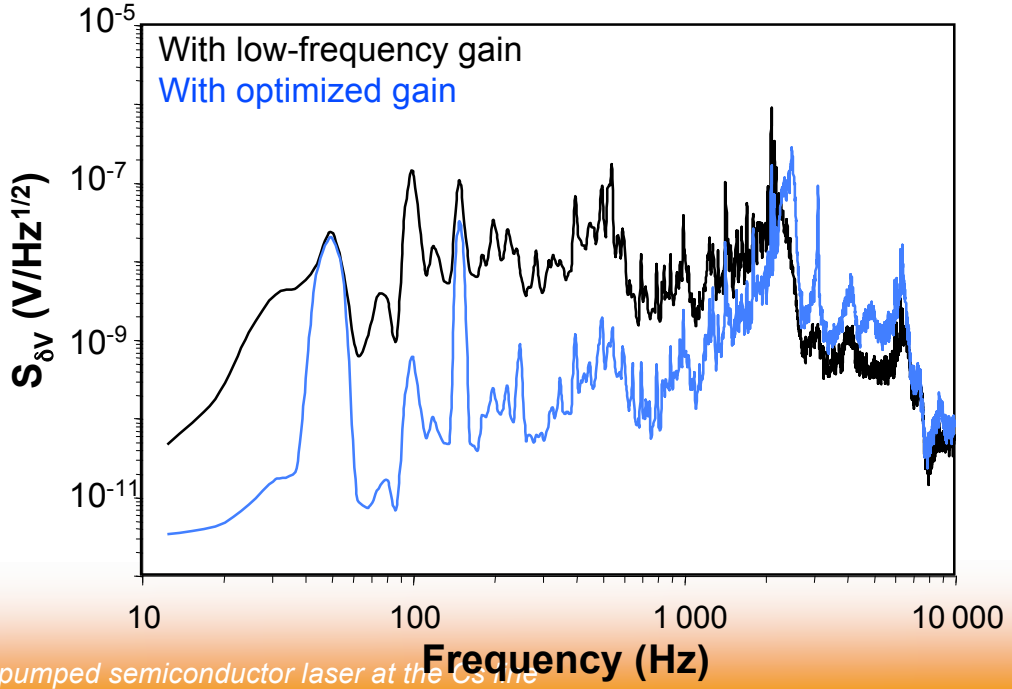
Beat-note set-up



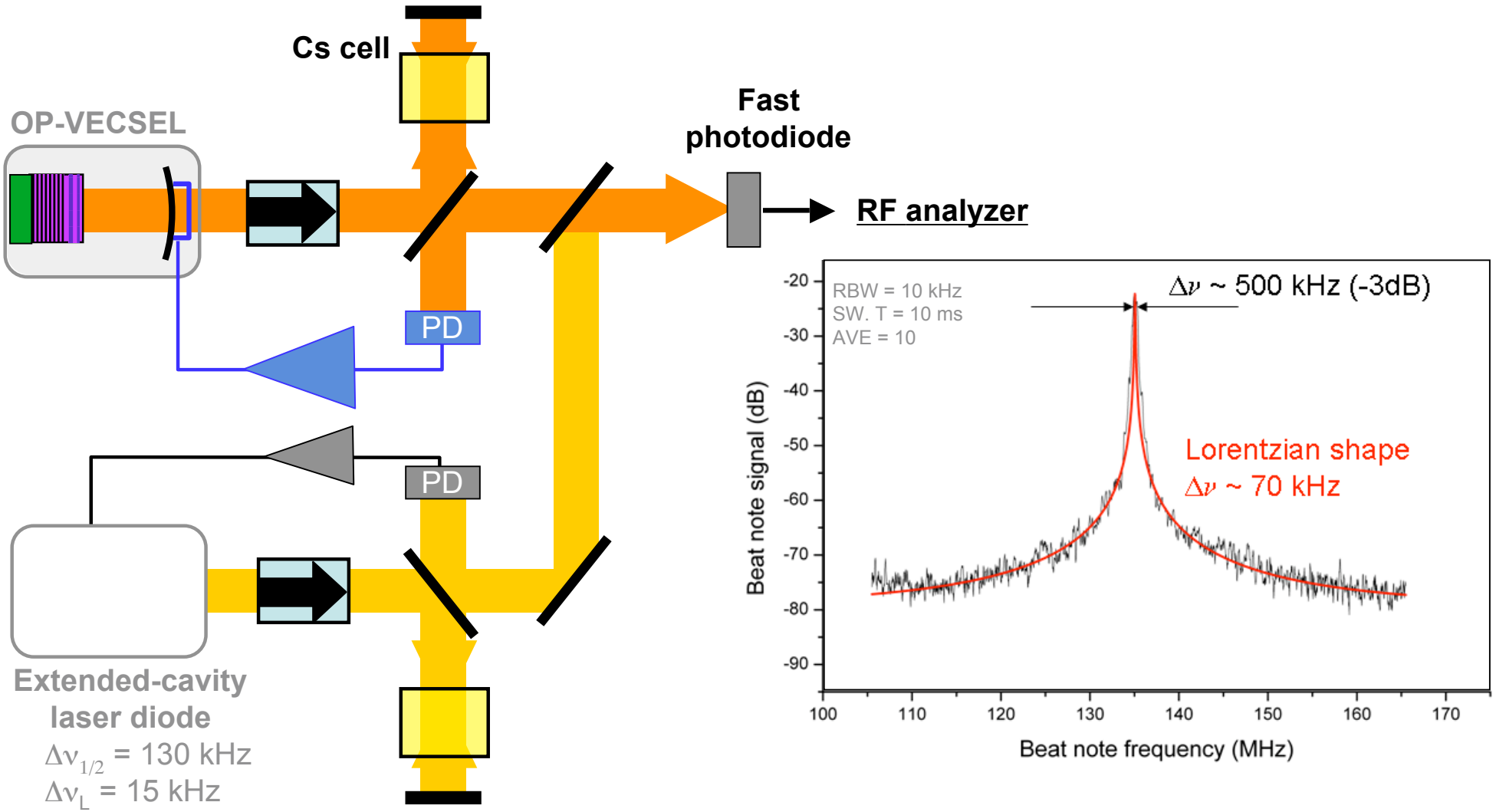
Baillard et al, Opt Comm (2006)

Stabilization of the laser frequency

- at side of a Doppler-free Cesium line (5 MHz FWHM)
- on PZT voltage - 2-stage integration electronics
- low-frequency servo loop (F < 2 kHz)

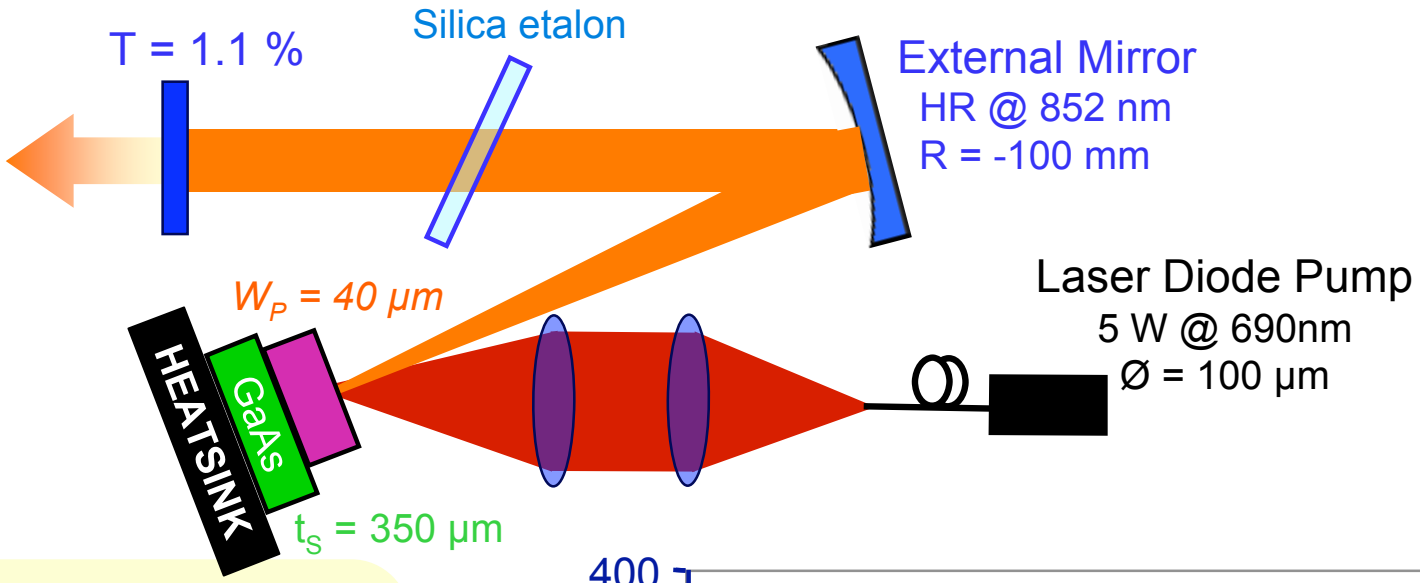


Linewidth measurement



- FWHM linewidth ≅ 500 kHz : low-frequency noise contribution
- Lorentzian linewidth ≅ 70 kHz related to white noise floor

Towards higher power…

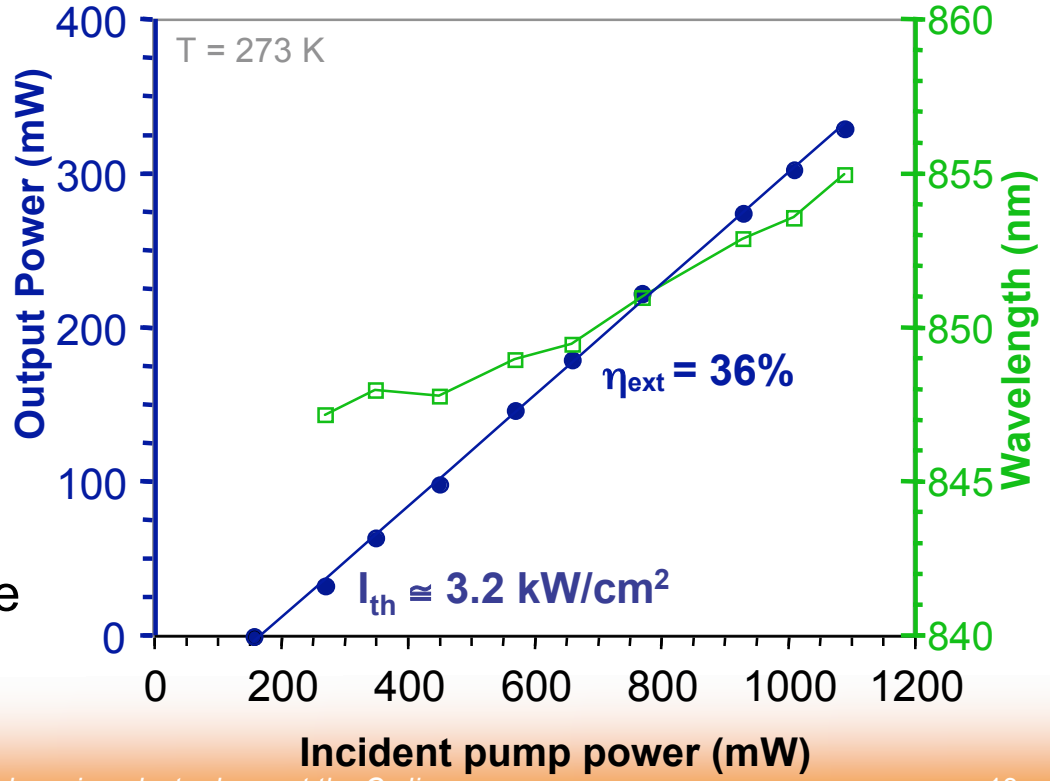


- **330 mW at P_P = 1.1 W**
  λ = 855 nm ($\Delta\lambda \cong$ 1 nm)
  450 mW under QCW pumping
- **Single transverse mode**
- **120 mW single-frequency**

⇒ Thermal-limited output power

⇒ **High output power** on a GaAs substrate

⇒ Low threshold & high opt-opt efficiency



Conclusion

– Design & fabrication of a AlGaAs/GaAs structure at λ = 852 nm optimized for low power/high efficiency operation

7 QWs

low threshold $I_{th} \leq 4$ kW/cm^2

– Single-frequency operation in a simple linear cavity

without λ-selective element : 17 mW

with a 25-µm thick etalon : 7 mW

} at 852.14 nm

– Validation on a Cs atomic line

>15 GHz continuous tunability

frequency lock-in on an absolute reference (*atomic line*)

comparison with an independent laser source :

$\Delta\nu_L$ = 500 kHz (-3dB / 10 ms *sweep time*)

Specifications already adequate for optical detection in atomic clocks

– Increase of the single-frequency power under high power pumping

120 mW without specific thermal management

(GaAs substrate, no intracavity heatspreader)

⇒ evaluation of the spectral properties

+ thermal management for power scaling