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

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Lasers in Cesium atomic clocks

Need for high-power and narrow-linewidth sources emitting at the Cesium D\textsubscript{2} line (852 nm)
⇒ a single OP-VECSEL?

Microwave interrogation:
F\textsubscript{Cs} = 9 192 631 770 Hz

Optical Detection
Δν << 5 MHz
Extended-cavity laser diodes

Cs atomic levels

Cs D\textsubscript{2} line
λ = 852 nm

9.192 GHz
F = 4

600 MHz
F = 5
F = 4
F = 3
F = 2

Scheme of an atomic fountain

Atom cooling
P\textsubscript{opt} > 200 mW
DFB/DBR diodes, MOPA, …
• 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, $\Delta \nu_L \approx 3$ kHz (Holm et al, IEEE PTL 11, 1551 (1999))

• Linearly polarized, circular TEM$_{00}$ beam
Design of the semiconductor structure

- $\lambda_L = 852$ nm
- Barriers absorption at $\lambda_P \leq 720$ nm
  $$e_b = 2 \, \mu m \Rightarrow \eta_P = 85\%$$

- AR coating ($Si_3N_4$) at air/SC surface for:
  - maximum pump transmission
  - reduction of microcavity etalon effect

- Structure grown by MOCVD
Design optimization

- Low threshold pump intensity $I_{th}$ for high opt-opt efficiency
  $\Rightarrow N_{QW} = 7$ is optimal for $\sim 2\%$ losses

<table>
<thead>
<tr>
<th>$T(°C)$</th>
<th>10°C</th>
<th>40°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g_0$(cm$^{-1}$)</td>
<td>1000</td>
<td>830</td>
</tr>
<tr>
<td>$I_{tr}$(W/cm$^2$)</td>
<td>105</td>
<td>190</td>
</tr>
</tbody>
</table>

Threshold intensity

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

- Compact plane-concave cavity: \( \text{L}_{\text{ext}} \approx 10 \text{ mm} \)
- Single-transverse mode pump laser diode:
  \[
  P_{\text{max}} = 120 \text{ mW (245 mA) at } \lambda_p = 658 \text{ nm}
  \]
- 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: $M^2 < 1.2$ and linear polarization

\[ P_L = 17 \text{ mW} \] (pump limited)

\[ \eta = 17\% \]

\[ I_{th} \approx 4.1 \text{ kW/cm}^2 \]
Single-frequency emission

- Single frequency operation **without intracavity \( \lambda \)-selective element**: checked with a high Finesse (\( F = 130 \)) 37.5-GHz-FSR scanning Fabry-Perot SMSR > 25 dB

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


Europhotons '08
With an intracavity etalon

25-µm thick (≈ 9 nm FSR) silica etalon
⇒ \( \lambda \) independent of operating conditions (T°, \( P_P \))
+ improved long-term stability

- Increased losses at \( \theta \neq 0^\circ \) ⇒ ↘ laser power: \( P_L = 7 \text{ mW @ 852.14 nm} \)
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

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)

With low-frequency gain
With optimized gain

Linewidth measurement

- FWHM linewidth \( \approx 500 \) kHz: low-frequency noise contribution
- Lorentzian linewidth \( \approx 70 \) kHz related to white noise floor
Towards higher power...

- 330 mW at $P_p = 1.1$ W
  $\lambda = 855$ nm ($\Delta \lambda \approx 1$ 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 $\lambda = 852$ 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 $\lambda$-selective element : 17 mW
  with a 25-$\mu$m thick etalon : 7 mW

– 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)

– 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

Specifications already adequate for optical detection in atomic clocks