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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 D2 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, $\Delta \nu_L \approx 3$ 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

InGaP Caping Layer (20 nm)

Active Layers $29\lambda/4$

Substrate GaAs 350 $\mu m$

Bragg Mirror

32.5 pairs $\lambda/4$
$Al_{0.22}Ga_{0.78}As/AlAs$
$R \geq 99.95\%$

$|E|^2$

Barriers

Quantum wells

GaAs
$N_{QW} = 7$ ; $L_{QW} = 8$ nm

Reflectivity $R_{\max} \approx 99.97\%$

Stop band 70 nm

Photoluminescence

Energy

0.0 0.2 0.4 0.6 0.8 1.0
0.6 0.7 0.8 0.9 1.0 1.1

Active Layers 29$\lambda/4$

InGaP Caping Layer (20 nm)
**Design optimization**

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

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**Experimental parameters**

<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: $L_{\text{ext}} \approx 10 \text{ mm}$
- Single-transverse mode pump laser diode:
  \[ P_{\text{max}} = 120 \text{ mW (245 mA)} \text{ at } \lambda_p = 658 \text{ nm} \]
- 52 x 52 x 58 mm$^3$ integrated setup for improved mechanical stability
Single-frequency diode-pumped semiconductor laser at the Cs line

- Low threshold: 4.1 kW/cm²
- Good beam quality: $M^2 < 1.2$ and linear polarization

**Output coupler**

$T = 1\% - R_C = 12 \text{ mm}$

- $P_L = 17 \text{ mW}$ (pump limited)
- $\eta = 17\%$
- $I_{th} \approx 4.1 \text{ kW/cm}^2$

![Graph showing output power vs. incident pump power and wavelength](image)
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

  \[
  t_{SM} \approx T_C \left( \frac{\Gamma}{FSR} \right)^2 \approx 1 \text{ms} \quad \text{for} \quad L_{ext} = 10 \text{ mm}
  \]

  \(T_C = \text{photon lifetime (\(~ 10 \text{ ns})}\)

  \(\Gamma = \text{gain bandwidth (\(~ 10 \text{ nm})}\)

  \(\text{Jacquemet et al., App. Phys. B (2006)}\)

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Europhotons '08

Single-frequency diode-pumped semiconductor laser at the Cs line
With an intracavity etalon

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

- Increased losses at \( \theta \neq 0^\circ \) ⇒ \( \downarrow \) 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)
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

Extended-cavity laser diode
$\Delta \nu_{1/2} = 130$ kHz
$\Delta \nu_L = 15$ kHz

RF analyzer

$\Delta \nu \sim 500$ kHz (-3dB)

Lorentzian shape $\Delta \nu \sim 70$ kHz
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

$\Rightarrow$ Thermal-limited output power

$\Rightarrow$ High output power on a GaAs substrate

$\Rightarrow$ Low threshold & high opt-opt efficiency

$T = 273$ K

$\eta_{ext} = 36\%$

$I_{th} \approx 3.2$ kW/cm$^2$

$\eta_{ext} = 36\%$
Design & fabrication of a AlGaAs/GaAs structure at $\lambda = 852$ nm optimized for low power/high efficiency operation

- 7 QWs
- low threshold $I_{\text{th}} \leq 4$ kW/cm$^2$

Single-frequency operation in a simple linear cavity

- without $\lambda$-selective element: 17 mW
- with a 25-µm 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
  ($GaAs\ substrate,\ no\ intracavity\ heatspreader$)

$\Rightarrow$ evaluation of the spectral properties
+ thermal management for power scaling

Specifications already adequate for optical detection in atomic clocks