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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$_2$ 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
  - 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$_3$N$_4$) at air/SC surface for:
  - maximum pump transmission
  - reduction of microcavity etalon effect

- Structure grown by MOCVD

$\eta = 85\%$

Active Layers
29$\lambda/4$

$|E|^2$

Bragg Mirror

$32.5$ pairs $\lambda/4$
Al$_{0.22}$Ga$_{0.78}$As/AlAs
R $\geq 99.95\%$

GaAs
350 $\mu m$

Substrate

GaAs

32.5 pairs $\lambda/4$
Al$_{0.22}$Ga$_{0.78}$As/AlAs
R $\geq 99.95\%$

$|E|^2$

Barriers

Al$_{0.22}$Ga$_{0.78}$As

Quantum wells

GaAs

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

InGaP
Caping Layer
(20 nm)

Reflectivity
$R_{max} = 99.97\%$

Stop band
70 nm

Photoluminescence

Energy
Design optimization

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

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/cm²)</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: $L_{\text{ext}} = 10 \text{ mm}$
- Single-transverse mode pump laser diode:
  \[ P_{\text{max}} = 120 \text{ mW} \text{ at } \lambda_p = 658 \text{ nm} \]
- $52 \times 52 \times 58 \text{ mm}^3$ 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

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

\[ I_{th} \approx 4.1 \text{ kW/cm}^2 \]

\[ \eta = 17\% \]
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 \( L_{ext} = 10\text{ mm} \)

\( T_C = \text{photon lifetime (~10 ns)} \)
\( \Gamma = \text{gain bandwidth (~10 nm)} \)

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

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)


![Graph showing beat-note set-up and stability measurements](chart.png)
Linewidth measurement

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

Extended-cavity laser diode
\[ \Delta v_{1/2} = 130 \text{ kHz} \]
\[ \Delta v_L = 15 \text{ kHz} \]

\[ \Delta v \sim 500 \text{ kHz } (-3\text{dB}) \]

Lorentzian shape
\[ \Delta v \sim 70 \text{ kHz} \]
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

⇒ 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-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)

⇒ evaluation of the spectral properties
+ thermal management for power scaling

Specifications already adequate for optical detection in atomic clocks