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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?
The document discusses a single-frequency diode-pumped semiconductor laser at the Cs line. The laser emits at 850 nm, with a Bragg mirror and an external mirror. Key features include:

- **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 ($\text{Si}_3\text{N}_4$) at air/SC surface for:
  
  maximum pump transmission
  
  + reduction of microcavity etalon effect

- Structure grown by MOCVD

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**Active Layers**

- $29\lambda/4$

**Stop band**

- $70$ nm

**Reflectivity**

- $R_{\text{max}} = 99.97\%$

**Photoluminescence**

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*Single-frequency diode-pumped semiconductor laser at the Cs line*
Design optimization

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

- Low threshold pump intensity \( I_{th} \) for high opt-opt efficiency
  \[ \Rightarrow N_{QW} = 7 \text{ is optimal for } \sim 2\% \text{ losses} \]
Single-frequency setup

- Compact plane-concave cavity: \( L_{\text{ext}} \approx 10 \text{ mm} \)
- Single-transverse mode pump laser diode:
  \[ P_{\text{max}} = 120 \text{ mW (245 mA) at } \lambda_p = 658 \text{ nm} \]
- 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

$P_L = 17 \text{ mW}$ (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 $t_{SM} = T_C \left( \frac{\Gamma}{FSR} \right)^2 \approx 1 \text{ ms}$ for $L_{ext} = 10 \text{ mm}$

$\begin{aligned}
T_C &= \text{photon lifetime (\sim 10 ns)} \\
\Gamma &= \text{gain bandwidth (\sim 10 nm)}
\end{aligned}$

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)
Single-frequency diode-pumped semiconductor laser at the Cs line

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)

Extended-cavity laser diode
$\Delta \nu = 130$ kHz

**Linewidth measurement**

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

**Extended-cavity laser diode**

- $\Delta \nu_{1/2} = 130$ kHz
- $\Delta \nu_L = 15$ kHz

**Cs cell**

**Fast photodiode**

**RF analyzer**

- $\Delta \nu \sim 500$ kHz (-3dB)
- Lorentzian shape $\Delta \nu \sim 70$ kHz

**OP-VECSEL**

**PD**

**Linewidth measurement**

- RBW = 10 kHz
- SW, T = 10 ms
- AVE = 10
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

$T = 1.1\%$

Silica etalon

$W_p = 40\ \mu m$

External Mirror
- HR @ 852 nm
- $R = -100$ mm

Laser Diode Pump
- 5 W @ 690 nm
- $\varnothing = 100\ \mu m$

$T = 273$ K

$\eta_{ext} = 36\%$

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

Europhotons '08