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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)

$\Rightarrow$ 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, $\Delta\nu_L \equiv 3$ 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
Design optimization

- Low threshold pump intensity $I_{th}$ for high opt-opt efficiency
  \[ I_{th} = N_{QW} I_{tr} \exp \left( \frac{T}{2 \Gamma N_{QW} L_{QW} g_0} \right) \]

\[ I_{th} = N_{QW} I_{tr} \]

$T$ (°C) | 10°C | 40°C
---|---|---
$g_0$ (cm$^{-1}$) | 1000 | 830
$I_{tr}$ (W/cm$^2$) | 105 | 190

$\Rightarrow N_{QW} = 7$ is optimal for ~ 2% losses
Single-frequency diode-pumped semiconductor laser at the Cs line

- Compact plane-concave cavity: $L_{\text{ext}} \approx 10 \text{ mm}$
- Single-transverse mode pump laser diode:
  \[ P_{\text{max}} = 120 \text{ mW (245 mA) at } \lambda_p = 658 \text{ nm} \]
- $52 \times 52 \times 58 \text{ mm}^3$ 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

![Diagram showing output power vs. incident pump power with a graph and key parameters: T = 280 K, $I_{th} = 4.1$ kW/cm², $\eta = 17\%$, $P_L = 17$ mW (pump limited).](image-url)
**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

λ = 852.14 nm (Cs)

• 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

- 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
\( \Delta \nu = 130 \text{ kHz} \)

Linewidth measurement

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

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

$\Rightarrow$ Thermal-limited output power
$\Rightarrow$ High output power on a GaAs substrate
$\Rightarrow$ Low threshold & high opt-opt efficiency

Europhotons '08
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 : $\Delta\nu = 500$ 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