Diode lasers for sensor applications

Bernd Sumpf
Ferdinand-Braun-Institut
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Outline

1. Diode Lasers – Basic Properties

2. Diode Lasers for Sensor Applications
   - Diode lasers with internal grating
   - Diode lasers in external cavities
   - Diode lasers as pump sources for non-linear frequency conversion
   - Hybrid integrated laser module for ps- and ns-pulses

3. Summary
Diode lasers – Features

- Wide spectral range: 0.34 nm ... 33 µm
  - FBH: 630 nm ... 1.2 µm
- High wall-plug efficiency
- Easy excitation
- Direct Modulation
- Small size
- Mechanical robustness
- Lifetime (> $10^7$ h)
- Tuneability
  - Current
  - Temperature
  - External grating

Compound Semiconductors
Laser diodes: High Output Power

Laser diode

\[ P = 20 \text{ W} \]
\[ 200 \mu \text{m} \times 2 \mu \text{m} \]

Power density
\[ p = 5 \text{ MW} / \text{cm}^2 \]

Coal-fired power plant

600 MW

Same power density in a 12 cm cable

Surface of the sun

6 kW / cm²
Laser Diodes: High efficiency

Efficiency \( \approx 73\% \)

Light bulb:  
\(< 5\%\)

Energy-saving lamp:  
\(< 20\%\)

\(\eta_c = 73\%\)
Laser Diodes: Narrow spectral linewidth

\[ \Delta \lambda_{\text{min}} \leq 10^{-6} \, \mu \text{m} \]

- Optical power \( P \) / arb. units vs. wavelength \( \lambda \) / \( \mu \text{m} \)
- Temperature \( T = 25^\circ \text{C} \)
- Power \( P = 400 \, \text{mW} \)

Planck's radiation spectrum

- Temperature: 10000 K, 5777 K, 3000 K, 1000 K, 500 K, 300 K, 100 K
- Spectral intensity: 10^10 to 10^4 W/(m²·µm)

3 cm

880 km

Paris - Berlin
Overview: Fabrication Process of a Laser Diodes

- Deposition of very thin crystalline layers on a GaAs substrate
  - Epitaxy

- Structuring of devices on the wafer
  - Processing

- Separation of single devices
  - Cleaving

- Mounting of devices on heat sinks

- Housing of devices
Schematic view of a high-power DFB laser

- Design epitaxial structure
- First epitaxy
- Manufacturing of the grating e.g. using holographic exposure
- Second epitaxy
- Process
- Facet coating
- Mounting

Resonator length
\[ L = 0.75 \text{ ... } 3 \text{ mm} \]

Ridge waveguide (RW)
\[ W_{RW} = 2 \text{ ... } 4 \text{ \mu m} \]
\[ \Delta n_{eff} \approx 3 \times 10^{-3} \]

AR coating
\[ R_f < 10^{-3} \]

Bragg Grating
Period = 150 \text{ ... } 300 \text{ nm}
Coupling coefficient
\[ \kappa = 1 \text{ ... } 10 \text{ cm}^{-1} \]
940 nm DFB lasers for H$_2$O absorption spectroscopy

Transmission measurement

- Tuneable Laser
- Lambert-Beers-Law

\[ I(\omega) = I_0 \cdot \exp[-\alpha(\omega) \cdot L] \]

- Threshold current \( I_{\text{th}} = 35 \text{ mA} \)
- Slope efficiency \( S = 0.9 \text{ W/A} \)
- Maximum output power \( P_{\text{max}} \approx 500 \text{ mW} \)
- Dips in the characteristic due to water absorption
940 nm DFB laser: Absorptions spectroscopy of water vapour

- Spectra calculated based on Lambert-Beers-law
- Comparison of calculated spectra to the data from the HITRAN database
- Excellent agreement
- Continuous tuning over 5 nm at one temperature
Diode lasers in external cavities for Raman spectroscopy

Raman measurement

- Fixed frequency laser (e.g. 488 nm, 671 nm, 785 nm)
  - Spectral emission width: $\Delta \nu \leq 10 \text{ cm}^{-1}$
  - Spectral stability $\delta \nu \leq 1 \text{ cm}^{-1}$
- Well-established contact free method
  - for material analysis, food safety control, clinical diagnostic.
- Excitation in the visual spectral range
  - Advantages:
    - Higher Raman signals due to a $\lambda^{-4}$ – dependence
    - Resonance Raman
    - Stokes lines in the maximum of the sensitivity of CCDs
  - Disadvantages:
    - Possible fluorescence background
- Shifted excitation Raman difference spectroscopy
  - Spectral distance for SERDS $\Delta \nu_{\text{SERDS}} \approx 10 \text{ cm}^{-1}$
671 nm microsystem light source

- **Gain medium:**
  - Broad area laser
    - \( w = 30 \mu m, 60 \mu m, 100 \mu m; \ L = 2 \text{ mm} \)
  - Output power up to 1.5 W
- **Resonator**
  - Front facet of the diode laser and Reflection Bragg Grating
  - Emission width below 100 pm (10 cm\(^{-1}\))
- **Active adjustment necessary**

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**Microoptical bench (13 mm x 4 mm)**

671 nm module – application in Raman-Spectroscopy

- Ethanol as analyte (A): Raman-signals spectrally resolved

- Fluorescent interference introduced (B)
  - Laser dye Cresyl violet

- Application of SERDS successful (C)
Diode lasers in external cavity for interferometry

Absolute distance interferometry (ADI) with $10^{-6}$ accuracy requires **tunable red emitting diode lasers**:

- Preferred wavelength $\approx 633$ nm
- Single-mode operation
- Tuning range $\geq 50$ pm (40 GHz)
  - Determines the smallest measurement distance about 4 mm
- Narrow spectral line width $\leq 10$ MHz (0.015 pm)
  - Determines the maximal measurement distance about 15 m
- Output power $\geq 5$ mW
- **Current tunable**, no moving parts

**Solution:**

- ECDL with **mode spacing** larger the spectral width of the RBG $\Delta \lambda_{RBG} \approx 50$ pm
  
  $n \ L \leq 4 \ mm \quad \Rightarrow \ \Delta \lambda_{FP} \geq 50$ pm - within RBGs spectral width only one mode!

- Narrow line width due to high quality resonator (High facet reflectivity)
Scheme of the external cavity laser

Single mode operation
- 34 pm, i.e. 25 GHz

Emission line width (self-delayed heterodyne)
- Between mode hops smaller 10 MHz
  ▶ coherence length of 30 m
- At mode hop increase to about 15 MHz

Side mode suppression ratio: Better than 25 dB
Diode lasers as pump sources for non-linear frequency conversion, e.g. SHG

Low power application (25 mW) for Raman spectroscopy

- Non-linear frequency conversion – Second Harmonic Generation (SHG)
  - Pump source
    → Distributed Feedback (DFB) RW Laser
  - SHG-crystal
    → periodically poled MgO:LiNbO₃ for 488 nm at 25°C
  - RW-SHG-Waveguide (3 µm x 5 µm x 11.5 mm)
    → higher efficiency

Microoptics

CuW-submount

Microbench (25 mm x 5 mm)
Diode lasers for the generation of ps- and ns-pulses

Methods:

- **Gain switching**
  - Current injection
  - Pulse length: 1 ns – 1 s
- **Q-switching**
  - Changing the properties of the laser cavity
  - E.g. implementation of an absorber section
  - Pulse length: 50 ps – 150 ps
  - Rep. Rate: up to 0.5 GHz
- **Mode locking**
  - Coupling of longitudinal modes
    - Passively (saturable absorber section)
    - Actively
  - Pulse length: 1 – 20 ps
  - Resonator length determines the rep. rate in the GHz-range
Gain Switching – DFB laser

- Geometry: \( L = 2 \text{ mm}, W = 6 \mu \text{m} \)
- Pulse length: \( 10 \text{ ns} \ldots 1 \text{ ms}; \text{ Rep. rate} 1 \text{ MHz} \)
- DFB laser with \( P_{\text{opt}} = 2 \text{ W} \) at \( I = 4 \text{ A} \)
- MOPA system with up to \( P_{\text{opt}} = 10 \text{ W} \)

\[
\tau_{\text{pulse}} = 10 \text{ ns}, \quad f_{\text{rep}} = 1 \text{ MHz}
\]

\[
\begin{align*}
\text{Pulse power P / W} &
\begin{cases}
0 & \text{I = 0.80 A, P = 0.52 W} \\
25 & \text{I = 1.80 A, P = 1.05 W} \\
50 & \text{I = 2.80 A, P = 1.53 W} \\
75 & \text{I = 4.00 A, P = 2.02 W}
\end{cases} \\
\text{Pulse current I / A} &
\begin{cases}
0 & \text{I = 0.80 A, P = 0.52 W} \\
25 & \text{I = 1.80 A, P = 1.05 W} \\
50 & \text{I = 2.80 A, P = 1.53 W} \\
75 & \text{I = 4.00 A, P = 2.02 W}
\end{cases}
\end{align*}
\]
Q-Switching – Multi-Section RW- and DBR Lasers

e.g. 3 – section DBR laser with gain, absorber, and grating section – length 1.5 ... 4.0 mm

- Current through gain section varied
- Output power can be modulated using the absorber section
  - \( V_{SAB} = -2.0 \text{ V} \); \( t_{\text{mod}} = 1 \text{ ns} \); \( f_{\text{rep}} = 40 \text{ MHz} \)
- Pulse length \( \leq 100 \text{ ps} \)
- Pulse power \( \approx 300 \text{ mW} \)
- Amplified power: 20 W
Monolythic devices for mode locking

4 section DBR-Laser
- DBR grating determines wavelength
- Fast saturable absorber for mode locking
  - Passive and active mode locking possible
- Round trip: ~ 230 ps, rep. rate ~ 4.3 GHz
- Pulse length ~ 8 ps, Jitter: < 1 ps
- Peak power: 1 W at 8 ps Pulse length
MOPA system with tapered amplifier for Q-switched ps-pulses

- **Master Oscillator:** Q-switched DBR
- **Power Amplifier:** Tapered Laser
  - Amplification of short pulses
  - Maintaining Beam Quality
  - Separate Excitation of RW and Tapered Section

**Generation of current pulses**
- **MO** < 1 ns, ≤ 1 A
- **PA** < 2 ns, ≤ 20 A

Electronics also developed at FBH
Results: MOPA system for Q-switched ps-pulses

- Pulse length (FWHM) = 73 ps
- Pulse power: 20 W
- Wavelength defined by MO with emission width (FWHM ~ 0.2 nm)
Pulse picking using tapered amplifier

Basic principle:

- RW-section of TPA as selector
  - Transparent or absorbing
  - Controlled with GaN-HF-transistor
  - Selectable duty cycle
- Amplification in tapered section

Diagram:
- Master oscillator
- DBR cavity gain absorber
- Amplifier section RW-section for gating
- HF transistor
- U<sub>CTR</sub> G D S
- Low frequency pulses 1kHz - 100MHz
- Pulse picker element
- High frequency pulses (GHz)

Graphs:
- Power / a.u. vs. time / ns
  - f active ML = 4.32399GHz
  - Pulse picker f/64 ~ 67MHz
Pulse picker – optical micro bench

- Integration of
  - optical elements
  - high-frequency electronics
    - 500 mA current pulses
    - 200 ps pulse width
    - Adjustable rep. rate
      - 1 kHz – 333 MHz
    - Jitter smaller 25 ps
- Small inductivity – short wires

GaN high electron mobility transistor HEMT

1cm DBR Laser

HF Ansteuerung Modenkopplung

HF Ansteuerung Pulspicker

Pulspicker mit HF Transistor

Auskoppeloptiken
Summary and Acknowledgments

Diode lasers:
- Compact, reliable, high-power light sources for different applications
- Features can be optimized with respect to the application:
  - Wavelength
  - Power
  - Emission width
  - Beam quality
  - Pulse parameter

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