Recent advances in high-performance 2.X μm Vertical External Cavity Surface Emitting Laser (VECSEL)

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Applications of 2.X μm VECSEL

- Medical therapy and diagnostics
- Materials processing  
  (e.g. welding of transparent plastics)
- Remote sensing  
  (e.g. wake-vortex detection)
- Directed infrared countermeasures  
  (DIRCM)
- Optical pumping of solid-state lasers  
  (e.g. ZnSe:Cr²⁺) and OPOs
- Seeding of solid-state lasers and OPAs
Semiconductor disk laser: Basic setup

- **VECSEL** = Vertical **External** Cavity Surface Emitting Laser
- **(OP)SDL** = Optically Pumped Semiconductor Disk Laser
Semiconductor disk laser: Basic setup

- **VECSEL** = Vertical External Cavity Surface Emitting Laser
- **(OP)SDL** = Optically Pumped Semiconductor Disk Laser

**Advantages:**
- circularly symmetric TEM$_{00}$ output possible → high brightness source
- Semiconductor QW active region → wide wavelength coverage → efficient pump absorption (no pump recycling optics) → compact laser modules
- Intra-cavity optical elements yield → short pulse → narrow linewidth
GaSb-based semiconductor disk lasers

- (AlGaIn)(AsSb)-based VECSEL, grown by MBE
- 2 – 3 µm wavelength range
GaSb-based semiconductor disk lasers

- (AlGaIn)(AsSb)-based VECSEL, grown by MBE
- 2 – 3 µm wavelength range
- Intra-cavity heatspreader (SiC or diamond) for efficient heat extraction
GaSb-based semiconductor disk lasers

**Active region**
- Barrier and spacer layer
- QWs

**Window layer**

**DBR-mirror**
- 21 pairs GaSb/AlAsSb

- Al$_{0.3}$GaAsSb barriers optimized for 980 nm pumping
- > 90% pump absorption
- Large quantum deficit > 50%
- Internal heating limits performance
2.0 µm VECSEL – CW lasing characteristics

- 2.0 µm SDL
- ternary GaInSb QWs
- SiC heatspreader
- diode pumped @ 980 nm

- 4.5 W, CW, 20 °C
- $\eta_{\text{diff}} = 20 \%, 20 \degree \text{C}$
- 6 W, CW, 0 °C
2.0 µm VECSEL – CW lasing characteristics

- 2.0 µm SDL
- Ternary GaInSb QWs
- SiC heatspreader
- Diode pumped @ 980 nm
- 4.5 W, CW, 20 °C
- η_{diff} = 20 %, 20 °C
- 6 W, CW, 0 °C
- Output power limited by heat extraction from active region
Active region design: reducing the quantum deficit

- Quantum-deficit: $> 50\%$
- Pump absorption efficiency: $> 90\%$

**Barrier pumping @ 980 nm**
Active region: reducing the quantum deficit

- Quantum-deficit: > 50 %
- Pump absorption efficiency: > 90 %

Barrier pumping @ 980 nm

In-well pumping @ 1.9 µm

~20 %
30 %
Active region: reducing the quantum deficit

- **Barrier pumping @ 980 nm**
  - Quantum-deficit: > 50 %
  - Pump absorption efficiency: > 90 %

- **Barrier pumping @ 1.5 µm**
  - Quantum-deficit: ~30 %
  - Pump absorption efficiency: > 90 %

- **In-well pumping @ 1.9 µm**
  - Quantum-deficit: ~20 %
  - Pump absorption efficiency: 30 %
Active region: reducing the quantum deficit

- **Quantum-deficit:** > 50 % ~ 30 % ~ 20 %

- **Pump absorption efficiency:** > 90 % > 90 % 30 %

- **Pump laser diode:**
  - **diff. efficiency** $\eta_d$ 80 % 45 % 20 %

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**Barrier pumping**
- @ 980 nm

**Barrier pumping**
- @ 1.5 µm

**In-well pumping**
- @ 1.9 µm
Active region: reducing the quantum deficit

- **Barrier pumping @ 980 nm**
  - Quantum-deficit: > 50 %
  - Pump absorption efficiency: > 90 %
  - Pump laser diode: diff. efficiency $\eta_d$ 80 %

- **Barrier pumping @ 1.5 µm**
  - ~30 %
  - > 90 %
  - 45 %

- **In-well pumping @ 1.9 µm**
  - ~20 %
  - 30 %
  - 20 %

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New VECSEL structures
→ GaSb barriers
→ diode pumped @ 1.5µm

Ternary GaInSb QWs
SiC heatspreader

7.2 W, CW, 20 °C
η_{diff} = 29 %, 20 °C
η_{quant} = 39 %, 20 °C
2.0-µm VECSEL pumped @ 1.5 µm – CW lasing characteristics

- **New VECSEL structures**
  - GaSb barriers
  - diode pumped @ 1.5µm
- Ternary GaInSb QWs
- SiC heatspreader

- **7.2 W, CW, 20 °C**
  - $\eta_{\text{diff}} = 29 \%, \ 20 ^\circ \text{C}$
  - $\eta_{\text{quant}} = 39 \%, \ 20 ^\circ \text{C}$

- **10.5 W, CW, -10 °C**
  - TE-cooled
2. X µm VECSEL - wavelength coverage so far

- GaSb-based VECSEL
- SiC intracavity heatspreader
- CW operation
- emission wavelength: 1.9 - 2.8 µm
- 980 nm barrier pumping

Data at 20 °C
VECSEL structures with reduced quantum deficit

- GaSb-based VECSEL
- SiC intracavity heatspeader
- CW operation
- Emission wavelength: 1.9 - 2.8 µm
- 1.5 µm barrier pumping
- 2.0 µm
  - $P_{\text{max}}$: 4.2 → 7.2 W
  - $\eta_d$: 20 → 28%
- 2.1 µm
  - $P_{\text{max}}$: 3.0 → 5.3 W
  - $\eta_d$: 20 → 30%

Data at 20 °C
VECSEL structure with reduced quantum deficit

- GaSb-based VECSEL
- SiC intracavity heatspeader
- CW operation
- Emission wavelength: 1.9 - 2.8 µm
- 1.5 µm barrier pumping
- Lowering operating temperature to -10 °C (TE-cooled)
- 2.0 µm
  \[ P_{\text{max}}: 7.2 \rightarrow 10.5 \text{ W} \]
Exploiting cavity versatility: 2.05 µm single-frequency VECSEL with V-shaped cavity

- Heterodyne beat-note measurements using two identical VECSEL modules
- 1 W output power at 20 kHz (60 kHz) actively stabilized (free running) @ 100 µs sampling time
- Max. single-mode output power 2.2 W (3.2 W) @ 20 °C (3 °C) heatsink temp.
Exploiting cavity versatility: cavity dumped 2 µm VECSEL

- Electro-optically cavity dumped 2 µm VECSEL with 35 cm long cavity
- 3 ns pulses with 30 W peak power @ 20 ºC (100 nJ pulse energy) for repetition frequencies up to 1 MHz
Miniaturizing VECSEL technology: \( \mu \)-cavity VECSEL

- Top mirror coated onto SiC heatspreader
Miniaturizing VECSEL technology: µ-cavity VECSEL

- Top mirror coated onto SiC heatspreader
- Stable cavity due to gradient index lens (thermal effects)
Top mirror coated onto SiC heatspreader
Stable cavity due to gradient index lens (thermal effects)
$P_{\text{max}}$ for 1.5 $\mu$m pumping (@ 20 °C): 2.2 W (multi-mode)
750 mW (TEM$_{00}$)
Tunable with temperature (coarse & mode-hop free fine tuning)
Summary and Outlook

- (AlGaIn)(AsSb)-based VECSEL covering the 1.9 – 2.8 µm wavelength span demonstrated
- Multi-mode operation with 7.2 W (10.5 W) max. output power @ 20 °C (-10 °C) demonstrated
- Single-mode operation (<100 kHz linewidth) up to 2.2 W (3.2 W) output power @ 20 °C (3 °C)
- Cavity-dumped VECSEL with 3 ns 30 W pulsed output up to 1 MHz rep. rate demonstrated
- µ-cavity VECSEL with 2.2 W max. output power realized

- Next to come: 2.X µm VECSEL as pump source for Ho:YAG laser and ZGP OPO