Applications of Broadly Tunable MEMS-VCSELS

Peter J.S. Heim
October 18, 2019
Thorlabs

- Corporate Headquarters: Newton, NJ
- ~ 2000 employees globally
- Company type: Private

Alex Cable - President & Founder
Thorlabs - Manufacturing
Thorlabs Sites Worldwide

Serving customers globally from 13 locations in 9 countries

- Tokyo, Japan
- Shanghai, China
- Austin, TX
- Sao Carlos, Brazil
- Molndal, Sweden
- Ely, UK
- Maisons-Laffitte, France
- Lubeck, Germany
- Munich, Germany
- Ann Arbor, MI
- Sterling, VA
- Newton, NJ
- Jessup, MD

Corporate Headquarters
Thorlabs Locations
Warehousing and shipping centers
Thorlabs Quantum Electronics

**Guilford Road** 40,000 sqft
- 21,000 sq. ft of Clean Room

**Stayton Drive** 43,000 sqft
- 4,000 sq. ft of MOCVD Clean
- 14,000 sq. ft of Wafer Fab Clean Room planned

✓ State-of-the-art semiconductor manufacturing facilities dedicated to OEM and catalog customers.

✓ Staff of 160: 40% with PhDs or MS

✓ EPI thru Wafer FAB to full module production

✓ InP, GaAs, GaSb and LiNbO$_3$ device fabrication capability.

✓ ISO 9001:2015 certified

**Semiconductor Lasers from 0.7 µm to 13 µm**
Vertically Integrated Manufacturing

Epitaxial Wafer Growth
Wafer Fabrication
Test & Reliability
Opto-electronic Packaging
Module Production
Electro-optic Module
Packaged Chip

Capabilities that provide advanced supply-chain and manufacturing solutions for customers

Products with increasing complexity and value-addition made in Jessup, MD
Broad Range of Semiconductor Products

Gain Chips for Tunable Lasers

Laser Diodes – TO Can Package

Chip on Submount & C-Mount Laser Diode

High Power D-Mount Mount Packages

4.5 mm D-Mount

Gain Chip in Half Butterfly Package

Butterfly packaged Semiconductor Lasers and SLDs

Gain Chip in Half Butterfly Package

SOAs & Booster Optical Amplifiers (BOAs)

HHL Mid-IR Lasers

Mid-IR Turnkey Laser
Serving Broad Range of Customers

- **TELECOM**
  - Gain Chips
  - Tunable lasers
  - LiNbO3 Modulators
  - Semiconductor Optical Amplifiers

- **MEDICAL**
  - MEMS VCSEL Tunable Laser for OCT
  - Gain elements for tunable lasers
  - Super Luminescent Diodes
  - InP and GaAs Laser Diodes

- **DEFENSE**
  - QCL/ICLs
  - LiNbO3 Modulators
  - Laser Diodes
  - Test Targets

- **SENSING**
  - High-speed Optical Amplifier Switches (NIR): Cavity ring-down sensors
  - High Power laser diodes 780 nm: Raman spectroscopy or other remote sensing
  - QCL/ICLs for trace gas sensing
Tunable MEMS-VCSEL: Optically Pumped

150nm/11.4% tuning

100nm/9.4% tuning
MEMS-VCSEL
# Product Test Data Sheet

## 1300 nm Swept Wavelength VCSEL Sub-Module

**S/N:** 002  
**Test Time:** 05/17/2012  
**Tested By:** Phong  
**QA:** Passed

### Summary of Test Conditions (\(T_{VCSEL} = T_{PUMP} = 25^\circ C\))

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pump Current</td>
<td>(I_p)</td>
<td>160</td>
<td>mA</td>
</tr>
<tr>
<td>DC Bias</td>
<td>(V_{dc})</td>
<td>8</td>
<td>V</td>
</tr>
<tr>
<td>Modulation Amplitude (sine wave)</td>
<td>(V_{mp})</td>
<td>22.8</td>
<td>V</td>
</tr>
<tr>
<td>Drive Frequency</td>
<td>(f_{op})</td>
<td>200</td>
<td>kHz</td>
</tr>
</tbody>
</table>

### Absolute Maximum Ratings

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Ratings</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth</td>
<td>115</td>
<td>nm</td>
</tr>
<tr>
<td>Pump Current (^a)</td>
<td>200</td>
<td>mA</td>
</tr>
<tr>
<td>DC Bias (^2)</td>
<td>70</td>
<td>V</td>
</tr>
<tr>
<td>Modulation Amplitude</td>
<td>70</td>
<td>V</td>
</tr>
<tr>
<td>Case Temperature</td>
<td>15-230</td>
<td>°C</td>
</tr>
<tr>
<td>Drive Frequency</td>
<td>500</td>
<td>kHz</td>
</tr>
</tbody>
</table>

\(^a\) Submodule 002 uses a Higher Current Pump Laser

### Summary of Test Results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical Bandwidth</td>
<td>BW</td>
<td>101</td>
<td>nm</td>
</tr>
<tr>
<td>Optical Power (Average) (^a)</td>
<td>Pop</td>
<td>140</td>
<td>µW</td>
</tr>
<tr>
<td>Power Ripple (^a)</td>
<td>(\Delta P)</td>
<td>0.9</td>
<td>%</td>
</tr>
<tr>
<td>Polarization Switching (^a)</td>
<td>PS</td>
<td>PASS</td>
<td>P/F</td>
</tr>
<tr>
<td>Resonance Frequency</td>
<td>(f_{res})</td>
<td>325</td>
<td>kHz</td>
</tr>
<tr>
<td>Free Spectral Range</td>
<td>FSR</td>
<td>1244-1359</td>
<td>nm</td>
</tr>
</tbody>
</table>

### Static Measurements

| Min Static Power \(^a\) | \(P_{DC}\) | 80  | µW   |
| Min Static SMSR \(^a\)  | SMSRdc  | 52  | dB   |

\(^a\) Optical Power Increase = 1%/°C for TVcSEL at 100

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### Bivariate Fit of Power dBm By WL nm

[Graph showing bivariate fit of power dBm by wavelength (WL) nm]
# MEMS-VCSEL Swept Source Module

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Min</th>
<th>Typical</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center Wavelength</td>
<td>$\lambda_c$</td>
<td>1280 nm</td>
<td>1300 nm</td>
<td>1320 nm</td>
</tr>
<tr>
<td>Tuning Range (-10 dB)</td>
<td>$\Delta \lambda$</td>
<td>95 nm</td>
<td>100 nm</td>
<td></td>
</tr>
<tr>
<td>Average Output Power</td>
<td>$P_o$</td>
<td>20 mW</td>
<td>30 mW</td>
<td></td>
</tr>
<tr>
<td>Duty Cycle (Unidirectional Sweep)</td>
<td>$D$</td>
<td>40</td>
<td>70</td>
<td></td>
</tr>
<tr>
<td>Coherence Length</td>
<td>$L_{coh}$</td>
<td>&gt; 100 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scan Linearization Ratio (max/avg)</td>
<td>SLR</td>
<td></td>
<td></td>
<td>1.5</td>
</tr>
<tr>
<td>Side Peak Suppression Ratio</td>
<td>SPSR</td>
<td>50 dB</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Relative Intensity Noise (RIN) – Ortho-RIN</td>
<td>$RIN_{ORTHO}$</td>
<td></td>
<td></td>
<td>2%</td>
</tr>
<tr>
<td>Sweep Rate (examples)</td>
<td>$R_{sweep}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P/N SVM130-XXXX</td>
<td></td>
<td></td>
<td></td>
<td>50 kHz</td>
</tr>
<tr>
<td>P/N SVM131-XXXX</td>
<td></td>
<td></td>
<td></td>
<td>100 kHz</td>
</tr>
<tr>
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</tr>
<tr>
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<td></td>
<td></td>
<td></td>
<td>400 kHz</td>
</tr>
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<td></td>
<td></td>
</tr>
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- P/N SVM130-XXXX: 50 kHz
- P/N SVM131-XXXX: 100 kHz
- P/N SVM132-XXXX: 200 kHz
- P/N SVM134-XXXX: 400 kHz
A technique called optical coherence tomography (OCT) has been developed for non-invasive cross-sectional imaging in biological systems. OCT uses low-coherence interferometry to produce two-dimensional images of optical scattering from internal tissue microstructures.

- ~ 30 Million OCT imaging procedures annually
- OCT system market approaching $1B per year

Swanson and Fujimoto, Biomedical Optics Expr., 2017
Evolution of OCT

**Time-Domain OCT**
- Broadband Light Source
- Detector
- Coherent Light
- Displacement vs. Δz

**Fourier-Domain OCT**
- Reference
- Sample
- Optical Spectrum
- Wavelength vs. Δz

**Spectral-Domain OCT**
- Broadband Light Source
- Spectrometer
- Fourier Transform
- Frequency Swept Light Source

**Swept-Source OCT**
- Reference
- Sample
- Detector Signal
- Fourier Transform
- Time vs. Δz
Sensitivity Roll-off in Spectral Domain OCT

Spectral Domain OCT Research Prototype in Clinic - Sensitivity Drop

-2dB (0.7mm)
-10dB (1.8mm)
-25dB (3.0mm)
Increased Imaging Depth with SS-OCT

Swept-Source OCT (Short-Cavity Laser)

Spectral Domain OCT

Coherence Length = 13.5 mm

OCT Imaging Depth (mm)

Amplitude (dB)

Imaging Depth (mm)
Short Cavity Laser vs Tunable VCSEL

**Short Cavity Laser**

- Laser Longitudinal Modes
- Filter Function
- Laser Gain

**VCSEL**

- Laser Longitudinal Modes
- Laser Gain
Drastic Increase in Imaging Depth with MEMS-VCSEL

MEMS-VCSEL Ideal Swept Source for OCT

History

- Wu et al 1995 (Berkeley).
- Matsui et al 2003: 64nm tuning =4.1% (Coretek)
- Dudley et al 1994: wafer-fused InP/GaAs VCSELs (UCSB)
- MacDougal et al 1997: GaAs/AlxOy mirror (USC)

Fundamental Performance Advantages

- **Wide Tuning**: Short micron scale cavity creates large mode spacing (FSR) and wide fractional continuous single-mode tuning range >10%.
- **Fast Tuning**: Small mirror mass and *adiabatic tuning* enable >2 MHz tuning speeds over full tuning range.
- **Variable Speed**: Engineered air damping provides flat mechanical frequency response.
- **Narrow Linewidth**: Short cavity produces single mode operation and >100 meter dynamic coherence length. Significant for anatomic imaging, metrology, and LIDAR.
- **Wavelength Flexible** technology from 650-5000 nm using InP, GaAs, GaSb based gain regions.
- **Low-cost** enabled by wafer-scale fabrication and test.
Application Area - Ophthalmology

- Worldwide the largest market for OCT
  - 10,000's systems sold annually
  - 10,000,000's procedures annually
- OCT can be particularly helpful in diagnosing **macular degeneration** (AMD), detachments of the neurosensory retina and retinal pigment epithelium, optic nerve disorders such as **glaucoma**.

Courtesy of Thorlabs Lübeck
Application Area - Cardiovascular


www.brittanica.com
Other Developing Medical Application Areas

◆ Gastrointestinal
◆ Dermatology
◆ Dental
◆ Brain Imaging
◆ Kidney Transplant Evaluation
◆ Bone Imaging
OCT can be useful to determine:

- coating thickness
- inter and intra-coating homogeneity
- defects in substrate and coating

Koller et al., European Journal of Pharmaceutical Sciences (2011)
Meter Range OCT

(a) 976 nm pump 
1310 nm tunable emission
MEMS VCSEL
MEMS flexure mechanism
Top mirror
Bottom mirror
InP MQW gain material

(b) 8 x PD
PBSR
VOA
VOA
Ch 1 (I)
Ch 2 (Q)
TIA
TIA
TIA
Silicon PIC

(d) Amplitude (a.u.)

(e) Scanners

(f) Zero delay

Silicon PIC

I & Q Detection

20GHz bandwidth
50GSPS Scope
Imaging Cubic Meter Volume with Micron Resolution

Gas Sensing: 3.0 – 3.5 um
Moving to the Mid-IR: ARPA-E Monitor Program
Room Temp CW Operation Demonstrated: Feb 2018

Double-bonded device cross section

3364 nm emission

GaAs top mirror

Antimonide Type I active region

GaAs bottom mirror

GaAs substrate

1625 nm pump

Above and below threshold optical spectra

Power (dBm/nm)

Wavelength (nm)

Above threshold

Below threshold

AR 47 mW
AR 75 mW
NO AR 40 mW
NO AR 75 mW
Optically-pumped VCSEL Device Structure

Key features:
• GaSb-based core grown via MBE
• Superlattice at top and bottom of structure can be left intact, or sacrificially etched to adjust mode position for optimal overlap of standing wave peaks with QWs
Wide Tuning Across Wafer Variation

97nm

3.303 \text{um}  

3.34 \text{um}
Device Structure

- ZnSe/ThF₄ mirror
- GaAs/AlGaAs DBR: ~18um thick
- InAsSb
- GaSb
- 2 X 5 ICL gain stages
- Top contact
- Bottom contact

Graphs showing power vs current and voltage for different temperatures (16C, 18C, 20C, 22C, 24C, 26C)
3.3 um eVCSEL

- Successfully demonstrated RTCW eVCSEL at 3.343 um with maximum CW lasing temperature of 26C.

- Employed wafer-bonded GaAs/AlGaAs bottom mirror, 10 ICL stages in GaSb-based active region, and top deposited ZnSe/ThF4 mirror.

- Optical spectra appear single mode with tens of microwatts output power.

- No current aperture was employed resulting in at least 2/3 of current being wasted outside optical mode.

- Thermal tuning of 1nm/mA via bias current injection could enable methane detection.

- Next steps are increasing output coupling for more power, reducing wasted current to drop threshold, and incorporating MEMS tuning.
Electrically Pumped MEMS-VCSEL (eVCSEL)
Initial eVCSEL Testing

Electrically-Pumped MEMS-VCSEL

- Wafer-Scale Monolithic MEMS-VCSEL Chip
- 1060 nm CWL with >60 nm Tuning Range
- Co-Packaged with Optical Amplifier
- Output Power: >15 mW
- 14-Pin Butterfly Package
Initial eVCSEL Testing

Electrically-Pumped MEMS-VCSEL

- Wafer-Scale Monolithic MEMS-VCSEL Chip
- 1060 nm CWL with >60 nm Tuning Range
- Co-Packaged with Optical Amplifier
- Output Power: >15 mW
- 14-Pin Butterfly Package

Idea in the Works!
Hungry for Your Thoughts

800 kHz A-scan rate
Additional MEMS-VCSEL Requirements

- Reproducible oxidation of fully-oxidized semiconductor mirror: needed for broad tuning
- Precise centering of broadband dielectric mirror: needed for broad tuning
- Precise control of MEMS release layer: control zero-voltage wavelength
- Heterogeneous integration of diverse materials (including wafer bonding)
- Complex processing (~15 mask levels)
- Assembly processes (e.g. die bonding) can change performance from wafer-level testing
- Optical pumping: increases complexity of all test steps, including burn-in
Many OCT and spectroscopy applications can scale to much larger markets if laser costs can be significantly reduced (10x – 100x).

Monolithic MEMS-VCSEL has inherent capability to scale to lowest cost through wafer-scale integration.

Electrically-Pumped MEMS-VCSEL with same performance as current oVCSEL.

Low-cost packing: integration with OCT and wavelength control elements.
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