VCSELs and Optical Interconnects

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Outline

Part 1  VCSEL basics
- Physics and design
- Static and dynamic properties
- Applications

Part 2  Research highlights – VCSELs for optical interconnects
- Optical interconnects
- High speed and energy efficient VCSELs
- VCSEL arrays and integration
Semiconductor laser basics

Current injection in a forward biased pin-junction $\Rightarrow$ population inversion $\Rightarrow$ optical gain through stimulated emission

Band gap $\Rightarrow$ wavelength: $\lambda_0 = \frac{hc}{E_g}$

Semiconductor Fabry-Perot laser:

- Gain medium (active region) = smaller band gap material
- Pump = current
- Optical feedback = cleaved facets (mirrors)

Heterostructure $\Rightarrow$ confinement of carriers and photons (waveguide)

Optical confinement factor: $\Gamma = \frac{\int \int E_y^2(x, y) dx dy}{\text{active region}}$  

Material gain:  $g$  

Modal gain:  $g_m = \Gamma \cdot g$
VCSEL vs. EEL

**Edge emitting laser (EEL)**
- Horizontal resonator
- Edge emitting (cleaving needed)
- Elliptical beam
- "Large" gain and optical mode volumes (~$10^2 \, \mu m^3$)
- "High" current and "high" power (~$10^2 \, mW$) operation

**Vertical cavity surface emitting laser (VCSEL)**
- Vertical resonator
- Surface emitting (on-wafer testing and screening)
- Circular beam
- "Small" gain and optical mode volumes (~$10^0 \, \mu m^3$)
- "Low" current and "low" power (~$10^0 \, mW$) operation

**Beam profiles**
- EEL
- VCSEL
VCSEL building blocks

- Vertical resonator created by two DBRs separated by the active region
- Current injection through doped DBRs
- Aperture for transverse current and optical confinement
Active (gain) region

- Thin active layer (QW) ⇒ quantization of states ⇒ modified density of states
- Strained (lattice mismatched) active layer ⇒ modified density of states
  ⇒ Lower transparency carrier density ($\Delta n_{tr}$), higher differential gain at low carrier density

Gain vs. carrier density:

\[
\text{Bulk: } g_{\text{max}}(\Delta n) = g_0 \cdot (\Delta n - \Delta n_{tr}) \\
\text{Quantum well (QW): } g_{\text{max}}(\Delta n) = g_0 \cdot \ln \frac{\Delta n}{\Delta n_{tr}}
\]

Differential gain:

\[
\frac{dg_{\text{max}}}{d(\Delta n)} = g_0 \quad \frac{dg_{\text{max}}}{d(\Delta n)} = \frac{g_0}{\Delta n}
\]
Distributed Bragg reflectors

- N pairs of layers with different refractive index $n_1$ and $n_2$

- Each layer is a quarter wavelength thick at the Bragg wavelength:
  \[ d_1 = \frac{\lambda_0}{4n_1} \quad \text{and} \quad d_2 = \frac{\lambda_0}{4n_2} \]

- Reflections at all interfaces add in phase $\Rightarrow$ constructive interference $\Rightarrow$ large reflectivity at the Bragg wavelength

\[
R_{\text{max}} = \left( 1 - \frac{n_{\text{out}}}{n_{\text{in}}} \left( \frac{n_1}{n_2} \right)^{2N} \right)^2
\]

- The maximum reflectivity increases with the index contrast ($\Delta n = n_1 - n_2$) and the number of pairs ($N$)

- The spectral width (bandwidth) increases with the index contrast

Reflection characteristics of an Al$_{0.90}$Ga$_{0.10}$As/Al$_{0.12}$Ga$_{0.88}$As DBR ($\lambda_0 = 850$ nm)
Distributed Bragg reflectors (cont’d)

- Field penetration and phase of reflection are represented by a hard mirror placed at a distance $L_{\text{eff}}$ from the start of the DBR.

For highly reflecting DBRs:

$$L_{\text{eff}} \approx \frac{\lambda_B}{4 \cdot \Delta n}$$

where: $\lambda_B =$ Bragg wavelength

- Semiconductor DBRs have graded composition interfaces and are modulation doped to reduce resistance and optical loss (free carrier absorption).

Al$_{0.90}$Ga$_{0.10}$As/Al$_{0.12}$Ga$_{0.88}$As

p-DBR
The vertical resonator

Effective optical length of the resonator:

\[ L_{opt} = \bar{n}_{DBR1} \cdot L_{eff1} + \bar{n}_{active} \cdot L_{active} + \bar{n}_{DBR2} \cdot L_{eff2} \]

where

\[ \frac{1}{\bar{n}} = \frac{1}{2} \left( \frac{1}{n_1} + \frac{1}{n_2} \right) \]

in the DBRs

- \( L_{opt} \) very small (~ one wavelength) \( \Rightarrow \) large longitudinal mode spacing \( \Rightarrow \) only one longitudinal mode under the gain spectrum \( \Rightarrow \) single longitudinal mode laser!
- Small longitudinal optical confinement factor (1-2%), thin gain region (QWs) \( \Rightarrow \) high DBR reflectivities needed (close to 100%)
- Field antinodes (maxima) \( \Rightarrow \) strong interaction with the gain region (multiple QWs), resonant gain enhancement
- Field nodes (minima) \( \Rightarrow \) weak interaction with the medium (regions with high optical loss)
Transverse current and optical confinement

GaAs-based VCSELs (670 – 1100 nm)

- The number of transverse modes depends on the aperture size and the effective index difference
- Multiple transverse modes ⇒ multiple emission wavelengths (multimode VCSEL)
- Single transverse mode (LP01) ⇒ single emission wavelength (single mode VCSEL)

Transverse optical confinement factor:

\[ \Gamma_{\text{trans}} = \frac{\int \int E_y^2(x, y) \, dx \, dy \text{ within aperture}}{\int \int E_y^2(x, y) \, dx \, dy \text{ everywhere}} \]

- The transverse confinement factors are large (>95%)
Transverse current and optical confinement (cont’d)

InP-based VCSELs (1300 – 2000 nm), GaSb-based VCSELs (2000 – 3500 nm)
Threshold current, slope efficiency and power efficiency

From optical resonator simulations:
- Transmission loss through top DBR ($\alpha_{tr,\text{top}}$)
- Transmission loss through bottom DBR ($\alpha_{tr,\text{bottom}}$)
- Absorption loss in DBRs ($\alpha_{\text{abs}}$)
- Material gain at threshold ($g_{\text{th}}$)
- Free carrier absorption
- Gain balances loss

Threshold carrier density (QWs):
\[ g = g_0 \cdot \ln \frac{\Delta n}{\Delta n_{tr}} \quad \Rightarrow \quad \Delta n_{\text{th}} = \Delta n_{tr} \cdot e^{g_0/\eta_0} \]

Spontaneous recombination at threshold:
\[ R_{sp}(\Delta n_{\text{th}}) = A \cdot \Delta n_{\text{th}} + B \cdot \Delta n_{\text{th}}^2 + C \cdot \Delta n_{\text{th}}^3 \quad \text{(no stimulated emission)} \]

Spontaneous recombination rate at threshold:
\[ \frac{\eta_{\text{th}} I_{\text{th}}}{q V_{\text{ach}}} = R_{sp}(\Delta n_{\text{th}}) \quad \Rightarrow \quad I_{\text{th}} = \frac{q V_{\text{ach}}}{\eta_{\text{th}}} \cdot R_{sp}(\Delta n_{\text{th}}) \quad \text{where} \quad V_{\text{ach}} = N_{\text{QW}} L_{\text{QW}} \cdot \frac{\pi d^2}{4} \]

External differential quantum efficiency:
\[ \eta_d = \eta_i \cdot \frac{\alpha_{tr,\text{top}}}{\alpha_{tr,\text{top}} + \alpha_{tr,\text{bottom}} + \alpha_{\text{abs}}} \]

Slope efficiency (W/A):
\[ SE = \frac{\Delta P}{\Delta I} = \frac{hc}{q \lambda_0} \cdot \eta_i \cdot \frac{\alpha_{tr,\text{top}}}{\alpha_{tr,\text{top}} + \alpha_{tr,\text{bottom}} + \alpha_{\text{abs}}} \]

Power efficiency:
\[ \eta_p = \frac{P}{VI} \]

- $\eta_i$ = internal quantum efficiency
- $N_{\text{QW}}$ = number of QWs
- $L_{\text{QW}}$ = QW thickness
- $d$ = aperture diameter

![Graph](attachment:image.png)
Detuning and temperature dependence

- Emission wavelength set by the resonance wavelength
- Resonance wavelength and gain spectrum redshift with temperature
- Gain peak shifts ~3 times faster than resonance
  ⇒ Small temperature variation of the threshold current with proper detuning
VCSEL dynamics – damping

Intrinsic small signal modulation response:

\[ H_{int}(f) \equiv \frac{p(f)}{i_a} = \text{const} \cdot \frac{f_r^2}{f_r^2 - f^2 + j \frac{f}{2\pi} \gamma} \]

\( f_r = \text{resonance frequency} \); \( \gamma = \text{damping rate} \)

Resonance frequency and D-factor:

\[ f_r = D \cdot \sqrt{1-I_{th}} \quad ; \quad D = \frac{1}{2\pi} \sqrt{\frac{\eta I v_g}{q V_a}} \left( \frac{\partial g}{\partial \Delta n} \right) \]

Damping rate and K-factor:

\[ \gamma = K \cdot f_r^2 + \gamma_0 \quad ; \quad K = 4\pi^2 \left( \tau_p + \frac{\epsilon \cdot \chi}{v_g \left( \frac{\partial g}{\partial \Delta n} \right)} \right) \]

Damping limited modulation bandwidth:

\[ f_{3dB,damping} = \frac{2\pi \sqrt{2}}{K} \]
VCSEL dynamics – thermal effects and parasitics

Increasing current ⇒ increasing temperature (self heating) ⇒ saturation of photon density and resonance frequency ⇒ thermally limited bandwidth

\[ f_r = D(T) \cdot \sqrt{I - I_{th}(T)} \quad ; \quad D = \frac{1}{2\pi} \sqrt{\frac{\eta_i \Gamma g}{qV_a} \cdot \frac{\partial g}{\partial \Delta n}} \]

\[ f_{r,max} = \frac{1}{2\pi} \sqrt{\frac{v_g \cdot \partial g}{\partial \Delta n} \cdot S_{max}} \]

Major heat sources:
- DBR resistance
- Free-carrier absorption

Increasing frequency ⇒ modulation current shunted past active region ⇒ parasitics limited bandwidth

\[ H(f) = \frac{p(f)}{i_a \cdot v_s} = \text{const} \cdot \frac{f_r^2}{f_r^2 - f^2 + j \frac{f}{2\pi} \gamma} \cdot \frac{1}{1 + j \frac{f}{f_p}} \]

Major parasitics:
- DBR resistance
- Capacitance over oxide layer (GaAs) or reverse biased pn-junction (InP)
VCSEL dynamics – large signal modulation

Digital modulation: biasing above threshold + current pulses ("1" and "0")

“Eye-diagram”

VCSEL operating at 2 Gbit/s
VCSEL applications – datacom

- Lane rate up to 25 - 28 Gbit/s (Ethernet, Fiber Channel)
- Aggregate capacity up to 400 Gbit/s (16 x 25 Gbit/s) in parallel fibers
- Reach typically 1-100 m
- Multimode optical fiber (50 µm core)
- Wavelength: 850 nm (GaAs-based VCSELs)
VCSEL applications – sensing

- Major applications:
  - Optical navigation (computer mouse, finger navigation modules, gesture recognition, …)
  - Spectroscopy (e.g. gas sensing and analysis)
  - Optical encoding (digital encoding of e.g. linear and rotary positions)
  - ……

- Many sensing applications require spectral purity, coherence and/or focusing capabilities
  ⇒ single-mode and polarization stable VCSELs

- It is expected that a smartphone will contain up to ~10 VCSELs!
VCSEL applications – high power

- 2D integration of 1000’s of VCSELs enables >100 W low brightness VCSEL arrays
- Major applications:
  - Surface treatment (heating)
  - Illumination (night vision)
  - Laser pumping

VCSEL array top view
8 W VCSEL array
2D array of VCSEL arrays

400 W VCSEL emitter
9.6 kW VCSEL module

Beam profile of a 100 W VCSEL array

Philips Photonics
Princeton Optronics
Lasertel
Optical interconnects – developments

- Higher *capacity* and *bandwidth density* (SDM, WDM)
  - Lane rates: 25-28 Gbit/s $\Rightarrow$ 50, 56, 64, 100 … Gbit/s
  - Aggregate capacity: 400 Gbit/s (16 x 25 Gbit/s) $\Rightarrow$ multi-Tbit/s

- Higher *efficiency*
  - 10’s of pJ/bit $\Rightarrow$ 1 pJ/bit

- High *operating temperature* (85°C, at least)

- Longer and shorter *reach*
  - Datacenters are growing in size ($\sim$ 10³ m)
  - Migration closer to the onboard circuits ($\sim$ 10⁻³ – 10⁰ m)

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**Lane rate vs. Year**

- Ethernet
- Fiber Channel
- Infiniband

**Distance vs. Lane rate**

- Rack - rack
- Shelve - shelve
- Board - board
- Module - module

- Multimode optical fiber
- Polymer optical waveguide

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**Plot of Lane rate (Gbit/s) vs. Year**

- 2000-2020
- Legend: 
  - Ethernet
  - Fiber Channel
  - Infiniband

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**Diagram of VCSEL-based optical interconnects**

- Pluggable tranceiver
- Active optical cable
- Mid-board optical module

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**Datacenters**

- Facebook
- IBM
- Consumer electronics

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**Graph of Lane rate (Gbit/s) vs. Distance (m)**

- 10⁻² to 10³ m
- TE Connectivity
Optical interconnects – developments (cont’d)

- Higher speed optoelectronics and electronics + electronic compensation + multilevel modulation ⇒ higher lane rates
- Spatial and wavelength division multiplexing (SDM, WDM) ⇒ higher aggregate capacity and higher bandwidth density
High speed 850 nm VCSELs

- Speed optimized with respect to damping, thermal effects and parasitics
- Modulation bandwidth = 28 GHz @ 25°C and 21 GHz @ 85°C
- Data rates up to 47 (57) Gbit/s with limiting (linear) optical receiver
Impact of damping on VCSEL dynamics

- Modulation bandwidth: trade-off between resonance frequency and damping rate
- Eye quality and BER: trade-off between rise/fall times, modulation efficiency and jitter

\[
D = \frac{1}{2\pi} \sqrt{\frac{\eta_i \Gamma_v g}{qV_a} \left( \frac{\partial g}{\partial \Delta n} \right)}
\]

\[
K = 4\pi^2 \left( \tau_p + \frac{\varepsilon \chi}{v_g \left( \frac{\partial g}{\partial \Delta n} \right)} \right)
\]

- Highest bandwidth (K = 0.2 ns)
Transmitter integration – equalization

- Driver and receiver circuits with two-tap feed forward equalization (FFE)
- IBM SiGe BiCMOS 8HP (130 nm)
- 26 GHz VCSEL (Chalmers), 22 and 30+ GHz photodiode (Sumitomo)
- Error-free transmission over MMF up to 71 Gbit/s at 25°C and 50 Gbit/s at 90°C
Onboard polymer waveguide interconnect

- Polymer waveguide embedded in backplanes and circuit boards to interconnect boards and modules
- 25 GHz high power/high slope efficiency VCSEL
- 40 Gbit/s NRZ and 56 Gbit/s PAM-4 transmission over 1 m polymer waveguide
- Record speed-distance products (40 and 56 Gbit/s·m)
Speed and efficiency enhancement by strong confinement

- Half-wavelength optical resonator, oxide apertures close to and on either side of the active region
- Modulation bandwidth = 30 GHz
- Transmission at 25-50 Gbit/s with energy dissipation < 100 fJ/bit

short cavity, reduced photon lifetime (reduced damping)

low resistance, low optical loss DBRs

strained InGaAs/AlGaAs QWs

BCB

multiple oxide layers

low thermal conductance n-DBR

undoped GaAs substrate
Transverse and polarization mode control

- Surface micro/nano structures for transverse and polarization mode control
- Multi-mW single mode output power
- 20 dB orthogonal polarization suppression

**Diagram:**
- Oxide aperture Ø 6 µm
- Mode filter Ø 3 µm
- Sub-wavelength surface grating
- 120 nm grating period
High speed VCSEL for extended reach

- Integrated mode filter for single mode emission
- Reduced impact of chromatic dispersion
- Extended reach: 25 Gbit/s over 1300 m MMF, 20 Gbit/s over 2000 m MMF

VCSEL with integrated mode filter

Oxide aperture \( \varnothing 6 \mu m \)
Mode filter \( \varnothing 3 \mu m \)
19 GHz bandwidth
Multilevel modulation over VCSEL-MMF link

- Increased capacity through improved spectral efficiency
- Pulse amplitude modulation (PAM) – low complexity, low power consumption, good receiver sensitivity
- PAM-n modulation (n levels, log₂(n) bits/level)
- 30 Gbaud PAM-4 (60 Gbit/s) transmission over a 20 GHz link (no equalization, no FEC)
- 40 Gbaud PAM-4 (80 Gbit/s) with equalization and FEC (70 Gbit/s)
- 20 Gbaud PAM-8 (60 Gbit/s) with FEC (56 Gbit/s)
VCSEL arrays for multicore fiber interconnects

- Multicore, multimode optical fiber for increased capacity and bandwidth density
- 6-channel circular VCSEL array
- 40 Gbit/s/channel up to 80°C, 240 Gbit/s aggregate capacity
- No crosstalk penalty
Integrated transmitters for WDM optical interconnects

- Integration platform
  - Short wavelength compatible (high speed and high efficiency GaAs-based optoelectronics)
  - Wavelength multiplexing, drive electronics

- Monolithic multi-wavelength VCSEL array
  - Wavelength setting in a post-growth process
  - Hybrid (flip-chip) or heterogeneous integration
  - In-plane emission

Heterogeneous integration:
Multi-wavelength high-contrast grating VCSEL array

- High contrast grating (HCG) for wavelength setting in a planar post-growth fabrication process
- High, broadband and mode/polarization selective reflectivity
- Phase of reflection (resonance wavelength) controlled by grating parameters (duty cycle, period)
- 4 channels with ~5 nm channel spacing at 980 nm
- Single transverse and polarization mode
Si-integrated short wavelength VCSEL with a hybrid cavity

- GaAs-based half-VCSEL attached to a dielectric DBR on Si using adhesive BCB bonding
- Hybrid III-V/Si cavity
- Sub-mA threshold current, high slope efficiency
- 20 Gbit/s modulation

![Diagram of Si-integrated short wavelength VCSEL with hybrid cavity](image)

![Graphs showing characteristics of Si-integrated short wavelength VCSEL](image)