High Speed VCSELs and Optical Interconnects

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Optics & Photonics in Sweden 2014
11 - 12 November 2014
Chalmers University of Technology, Göteborg
Outline

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- VCSEL speed limitations
- VCSEL design for high speed
- Photon lifetime
- Performance
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Introduction

Vertical-Cavity Surface-Emitting Laser – VCSEL

- Surface emitting semiconductor laser with optical feed-back provided by highly reflective mirrors (DBRs)
- Small volume (10x10x10 µm$^3$) → low drive current, low power consumption
- Wafer scale production and testing (100 000 lasers on single 3” wafer possible) → low fabrication cost
- GaAs-based materials → emission at 850 nm wavelength

Bias current + data signal

DBR (p-type)

oxide aperture

DBR (n-type)

gain medium (MQW)

effective refractive index

index guiding of optical field

VCSELs probed on wafer

SEM image of high speed VCSELs
Introduction
Optical interconnect = short reach optical link for high capacity data transfer

Datacenters

High performance computing

DataCom

ComputerCom

Consumer links

Distance (m)

10^2 10^1 10^0 10^1 10^2 10^3

rack - rack
shelf - shelf
board - board
module - module

Multimode optical fiber
Polymer optical waveguide
VCSEL based optical interconnects

Optical Thunderbolt
Optical USB 3.0
Introduction

- Datacom is today the most rapidly growing segment of the optical communications market
- GaAs-based 850 nm wavelength VCSELs are key components

Warehouse-scale datacenters and supercomputers:

$\sim 10^6$ optical interconnects (2012) $\rightarrow$ $\sim 10^9$ optical interconnects (2020)

Requirements for datacom VCSELs:

- High speed
- High operating temperature
- Low power consumption
VCSEL speed limitations

Transmission at high data rates require a large modulation bandwidth

- The modulation bandwidth is limited by a combination of damping, electrical parasitics, and thermal saturation
  - These parameters can be tuned in the VCSEL design to optimize the modulation bandwidth
VCSEL design for high speed

- Thick polymer for reduced pad capacitance
- Multiple oxide layers for reduced capacitance
- Graded interfaces and modulation doping in DBRs
- AlAs in bottom DBR for improved thermal conductivity
- Active region optimized for rapid bandwidth increase with current

Chalmers 3rd generation high speed 850 nm VCSEL design

Photon lifetime

- The intrinsic high speed properties of the VCSEL depend strongly on the photon lifetime*
- The large refractive index step at the semiconductor/air interface has a strong impact on DBR reflectivity and photon lifetime
- Nanometer thinning of top layer $\rightarrow$ reduced mirror reflectivity and photon lifetime

*Photon lifetime = the lifetime of a photon in the laser resonator before it escapes

There exists an optimum photon lifetime for maximum modulation bandwidth

> 50% increase in modulation bandwidth achieved by optimizing the reflectivity of the top DBR
VCSEL-based optical interconnect

- limiting receiver
  - Gen 3, 7 µm aperture diameter, 26 GHz BW
    - Photon lifetime optimized for maximum modulation BW
  - VI-Systems R40-850 photoreceiver (~30 GHz BW, limiting TIA)
  - Error-free transmission: bit-error-rate (BER) < $10^{-12}$

VCSEL-based optical interconnect
- linear receiver

- Gen 3, 8 µm aperture diameter, 24 GHz BW
  - VCSEL has slightly higher damping (longer photon lifetime) \(\rightarrow\)
    flatter response \(\rightarrow\) reduced ringing and timing jitter*
- New Focus 1484-A-50 photoreceiver (22 GHz 3 dB BW, linear TIA)

*For more information, see Emanuel Haglund’s Poster "Optimum Damping Level for High-Speed Large Signal VCSEL Modulation"
VCSEL-based optical interconnect - equalization

- 26 GHz VCSEL (Gen 3 Chalmers), > 30 GHz photodiode (Sumitomo)
- Driver and receiver circuits with two tap feed forward equalization (FFE)
- IBM SiGe BiCMOS 8HP (130 nm)
- Error-free transmission over MMF up to 71 Gb/s at 25°C and 50 Gb/s at 90°C

VCSEL-based optical interconnect

- multi-level modulation
  - Increased capacity through improved spectral efficiency
  - Pulse amplitude modulation (PAM) – low complexity, low power consumption, good receiver sensitivity
  - PAM-4 modulation (4 levels, 2 bits/level)
  - 60 Gb/s (30 Gbaud) transmission over a 20 GHz link

25 Gbaud (50 Gbps)  30 Gbaud (60 Gbps)

Back-to-back

50/100 m OM4 fiber

VCSEL-based optical interconnect
-onboard polymer waveguide interconnect

- Polymer waveguide embedded in backplanes and circuit boards to interconnect boards and modules
- 40 Gb/s NRZ and 56 Gb/s PAM-4 transmission over 1 m polymer waveguide
- Record speed-distance products (40 and 56 Gbps·m)

VCSEL array for MCF links

- Multi-core optical fiber (MCF) for increased capacity and bandwidth density
  - 6-channel VCSEL array matched to MCF geometry
- 240 Gb/s (6×40 Gb/s) single fiber capacity

Summary

- VCSEL based links for datacom is the fastest growing segment of the optical communications market
- Approaching 30 GHz bandwidth for directly modulated 850 nm VCSELs
- Binary modulation:
  - 57 Gb/s at 25°C and 40 Gb/s at 85°C unequalized
  - 71 Gb/s at 25°C and 50 Gb/s at 90°C equalized
- Multi-level modulation
  - 60 Gb/s at 25°C
- VCSEL arrays
  - 6×40 Gb/s = 240 Gb/s over a single MCF
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Thank you!
Acknowledgement

The team at Chalmers

Anders Larsson
Johan Gustavsson
Jörgen Bengtsson
Åsa Haglund
Benjamin Kögel
Rashid Safaisini
Erik Haglund
Emanuel Haglund

Krzysztof Szczesna
Magnus Karlsson
Peter Andrekson

Johnny Karout (S2)
Erik Agrell (S2)

IQE Europe (UK)
Tyndall Institute (Ireland)
Technical University of Berlin (Germany)
Cambridge University (UK)
CNR-IEIIT (Italy)
IBM (USA)
HP Labs (USA)
Ghent University (Belgium)
ULM Photonics (Germany)
IHP (Germany)
OFS (Denmark)
VTT (Finland)

Financing

European Union (FP7 projects VISIT and MERLIN)
Swedish Foundation for Strategic Research (projects LASTECH, MuTOI)