25 Years VCSEL Research and Development at Ulm University and Philips Photonics

K.J. Ebeling, Institute of Optoelectronics, Ulm University

IISLC 2016, Kobe, Japan, Sept. 12, 2016

GaInAsP/InP Surface Emitting Injection Lasers,

Haruhisa SODA, Ken-ichi IGA, Chiyuki Kitahara, and Yasuharu Suematsu

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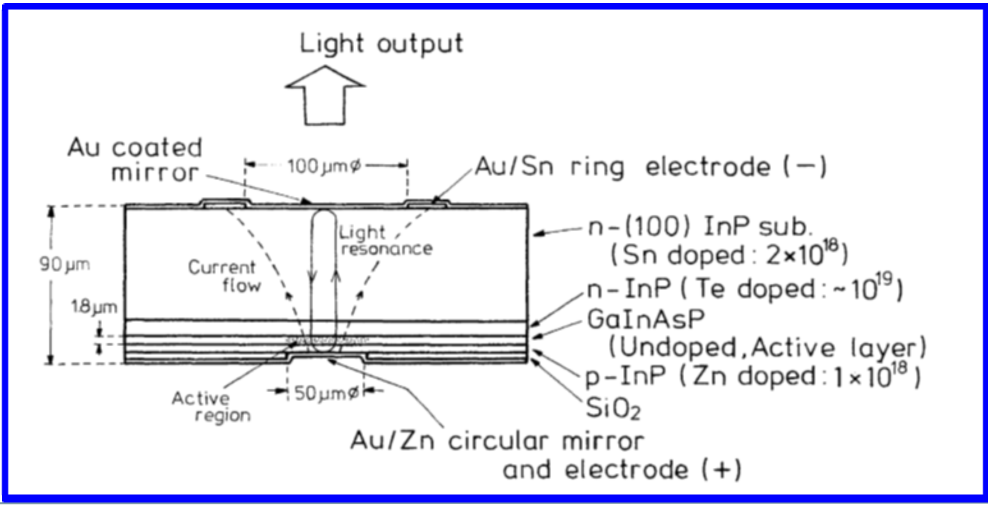
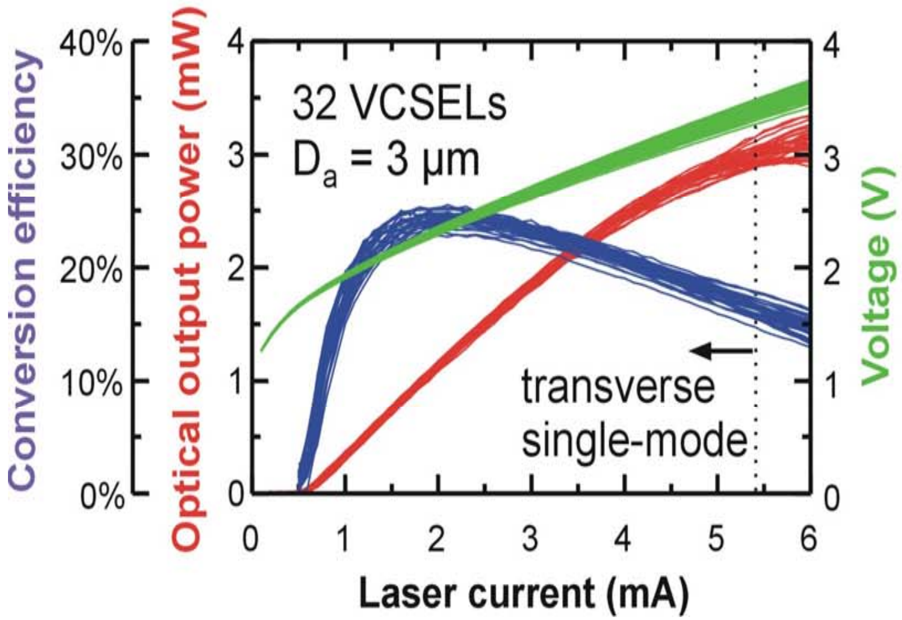
(Received August 6, **1979**)

1977
Entry in Iga's
lab notebook



2017
More than 1 billion
VCSELs shipped

Ulm Monolithic Bragg Reflector VCSELs



Threshold	1 mW output
I_{th} = 0.6 mA U_{th} = 1.7 V η_d = 64%	I = 1.9 mA U = 2.3 V η = 24%

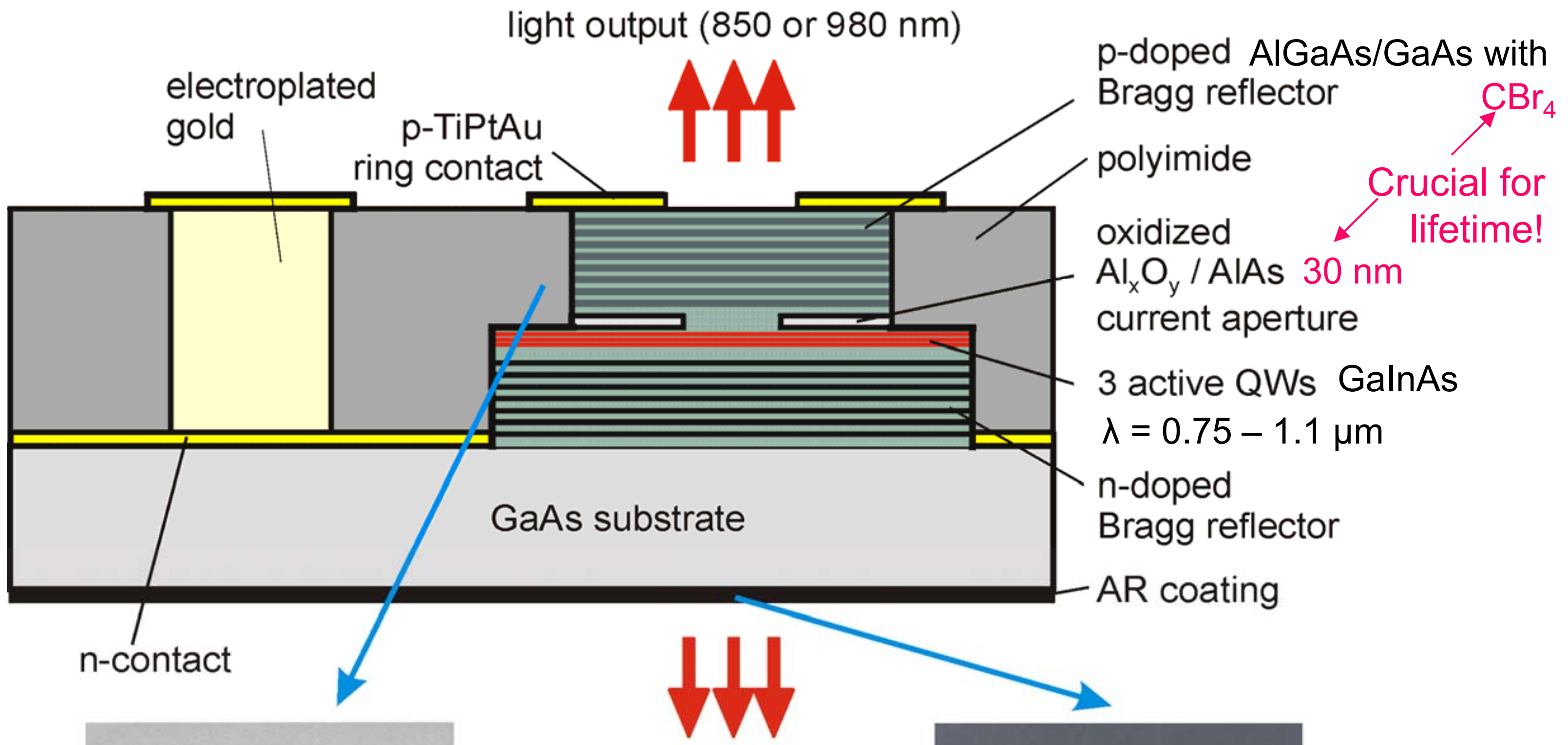
Prof. Iga inspecting Ulm University VCSEL demonstrator at ECOC, Berlin 1992

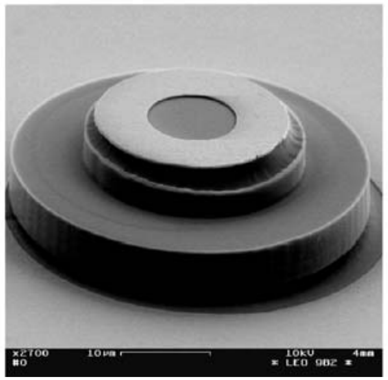
Iga: “shock proved VCSEL”

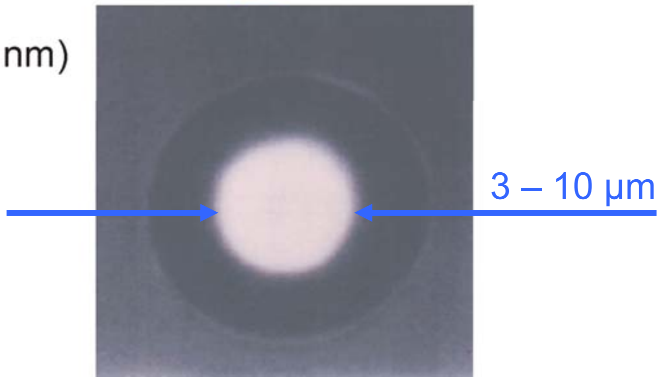
Institute of Optoelectronics

Ulm University

VCSEL with 30 nm Oxide Aperture and Carbon Modulation Doping

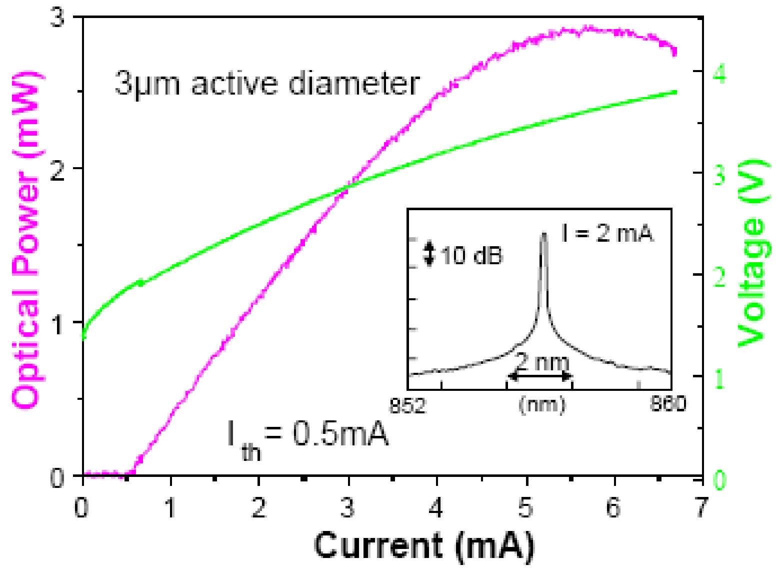


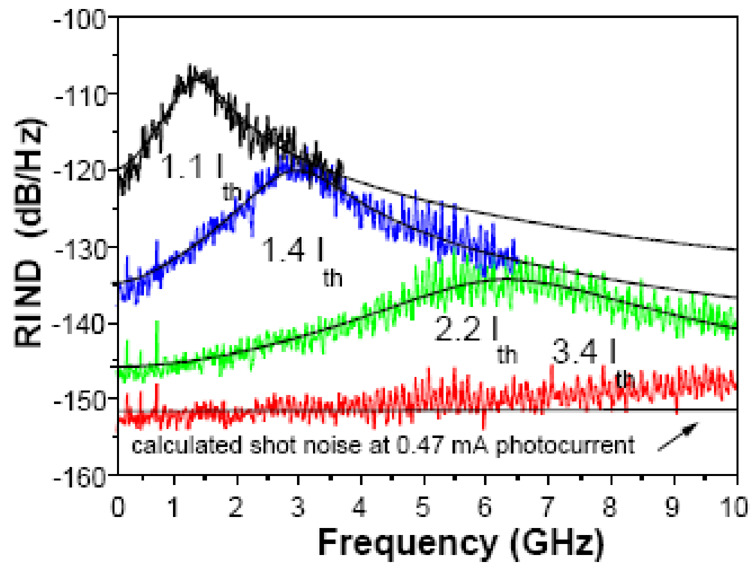




MBE Growth: Roland Jäger , Oxidation: Martin Grabherr

Characteristics of 3 µm Oxide Confined Single-Mode VCSEL





Intrinsic modulation limit: ν_{3dB} = 22 GHz

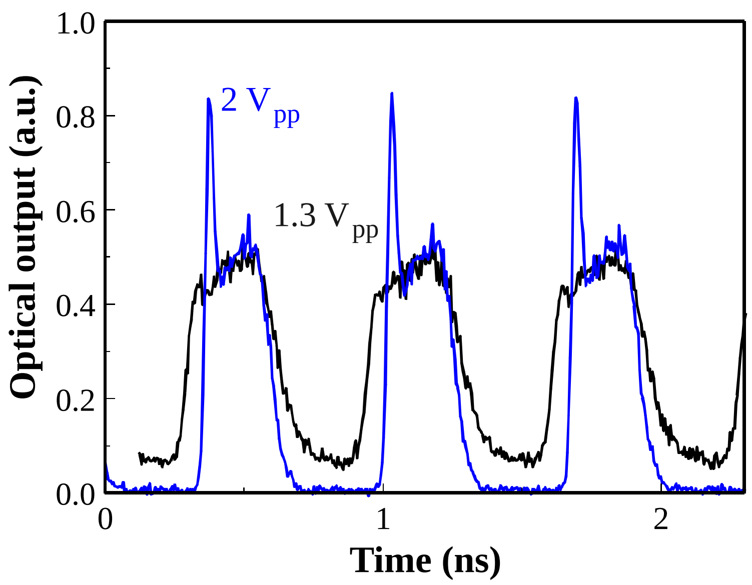
Properties:

Transverse side mode suppression > 30 dB
Orthogonal polarization mode suppression > 25 dB
Relative intensity noise close to quantum limit
Room temperature lifetime several years

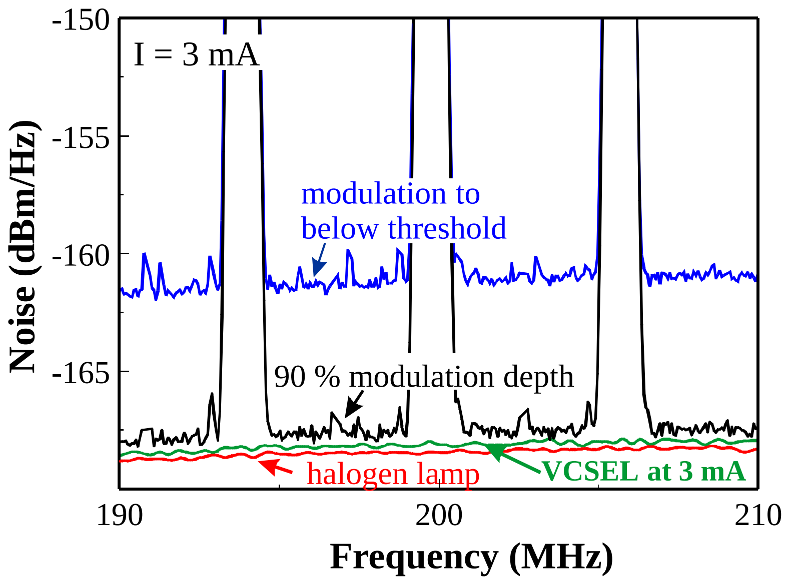
Device Processing: Roger King, Characterization: Dieter Wiedemann

Large Signal Modulation and Noise Characteristics of 3 µm Oxide Confined Single-Mode VCSEL

Output signals for 3 Gbit/s current modulation, biased 1.3 V_{pp}, bias-free 2 V_{pp}

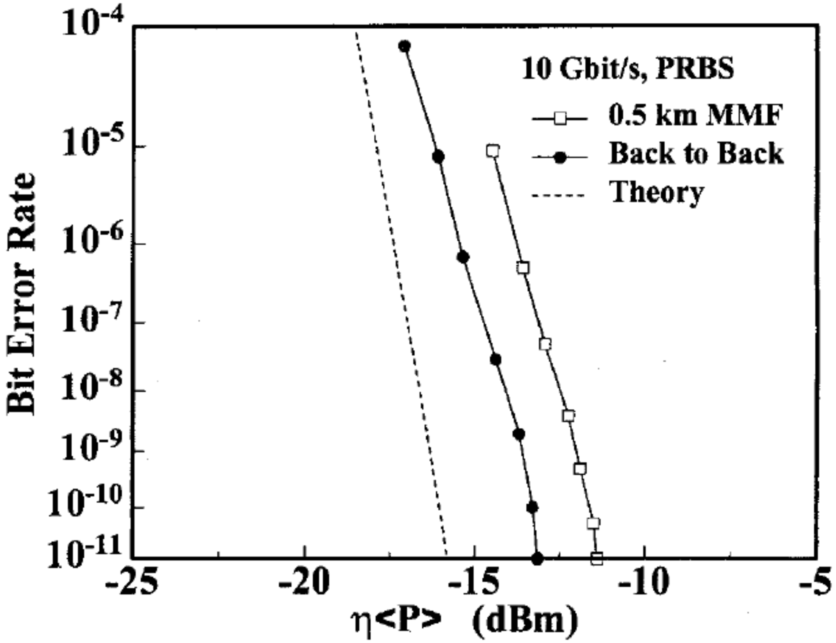


Spectra for pseudo random bit sequence modulation at 3 Gbit/s, word length $2^7 - 1$



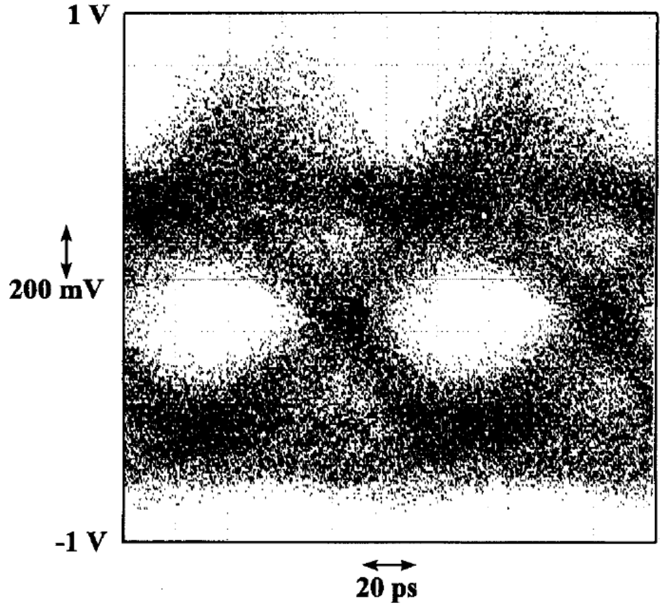
Early 10 Gbit/s Data Transmission with VCSEL over 500 m Multi-Mode Graded-Index Fiber

Bit error rate characteristics (PRBS 2^7 - 1)

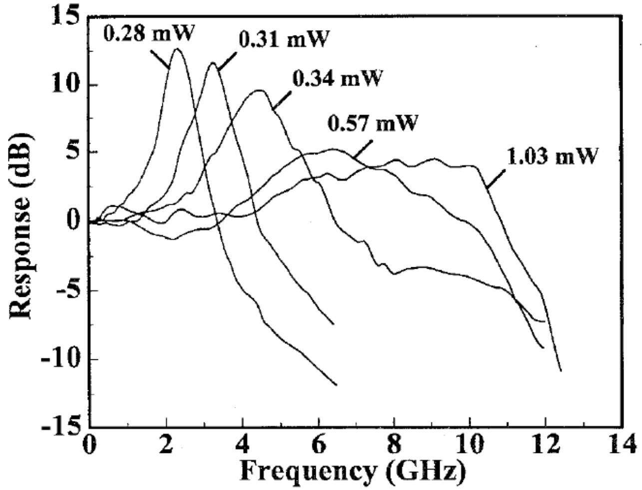


U. Fiedler et al., IEEE PTL 1996

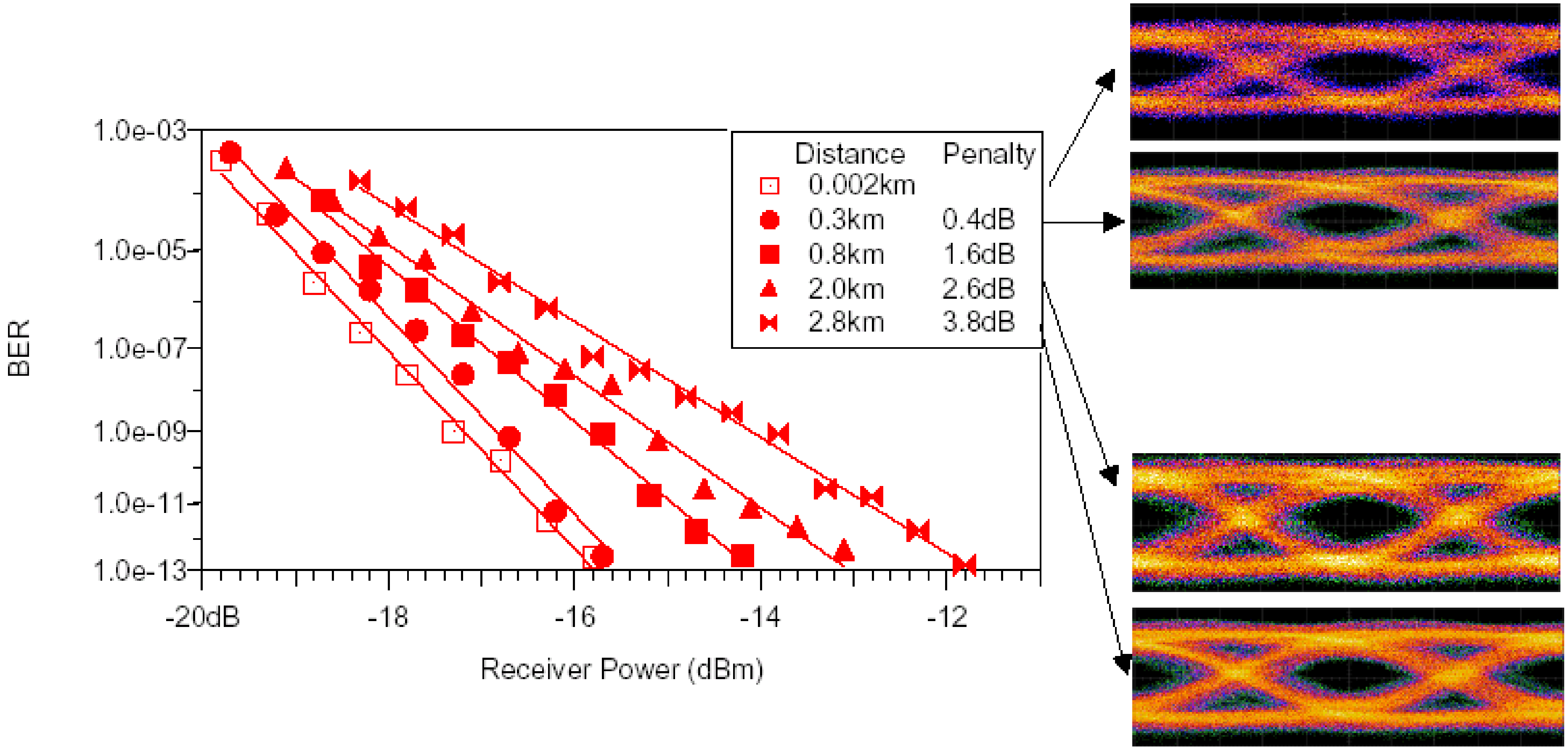
10 Gbit/s eye diagram at BER = 10^{-9}



Small signal frequency response

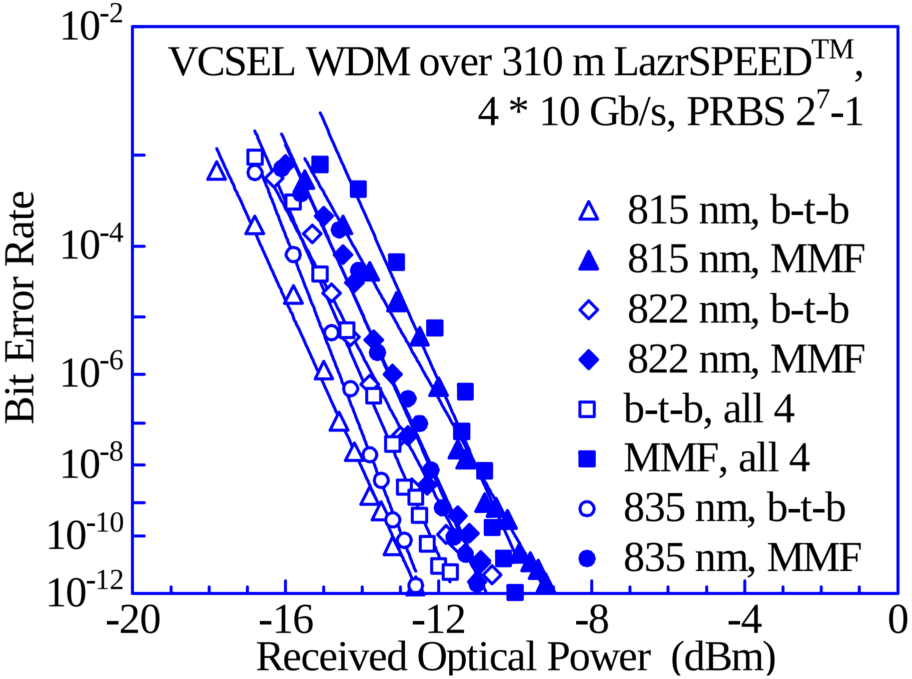


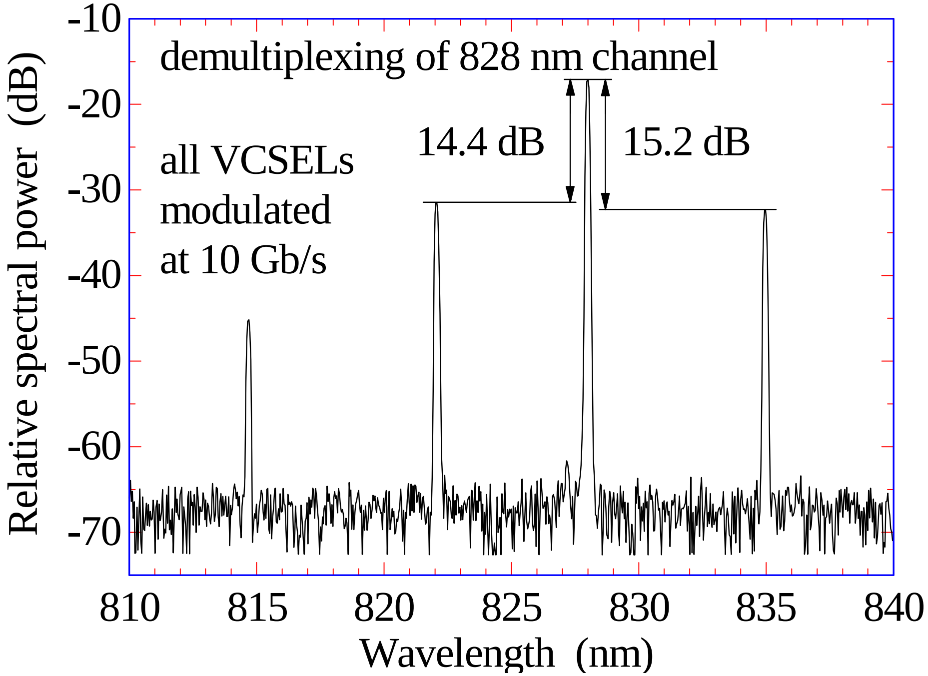
10 Gbit/s over 2.8 km High-Speed Multimode Fiber with 830 nm Single-Mode VCSEL



R. Michalzik et al., CLEO 2000, PD

40 Gbit/s Coarse WDM Data Transmission over 310 m High-Speed Multimode Fiber





R. Michalzik, ECOC 2000

Collaboration with Lucent Technologies
Bell Labs Innovations

Highlights of Fiber Data Transmission with VCSELs 1993-2000

Short Wavelength:

Year	Institution	Data Rate	Length	Type	Wavelength
1993	IBM, Bell Labs	3.0 Gbit/s	~1 m	MMF	980 nm
1994	UCSB	2.5 Gbit/s	30 m	MMF	980 nm
1995	University of Ulm	10.0 Gbit/s	500 m	MMF	850 nm
1995	University of Ulm	3.0 Gbit/s	4300 m	SMF	980 nm
1996	HP	10x622 Mbit/s	300 m	MMF	980 nm
1997	NTT	40x700 Mbit/s	100 m	MMF	850 nm
1998	Tokyo Inst. of Technol.	10.0 Gbit/s	100 m	MMF	980 nm
1998	NEC	3.0 Gbit/s	100 m	HCS	980 nm
1999	University of Ulm	12.5 Gbit/s	100 m	MMF	850 nm
1999	Lucent, University of Ulm	9.0 Gbit/s	100 m	GI-POF	850 nm
2000	Lucent, University of Ulm	10.0 Gbit/s	2800 m	MMF (n)	850 nm
2000	Lucent, University of Ulm	4x10.0 Gbit/s	310 m	MMF (n)	850 nm

Long Wavelength:

Year	Institution	Data Rate	Length	Type	Wavelength
1997	UCSB	2.5 Gbit/s	60 km	SSMF	1544 nm
1999	Opto+ Alcatel	2.5 Gbit/s	90 km	SSMF	1500 nm
2000	Bandwidth 9	2.5 Gbit/s	50 km	SSMF	1600 nm

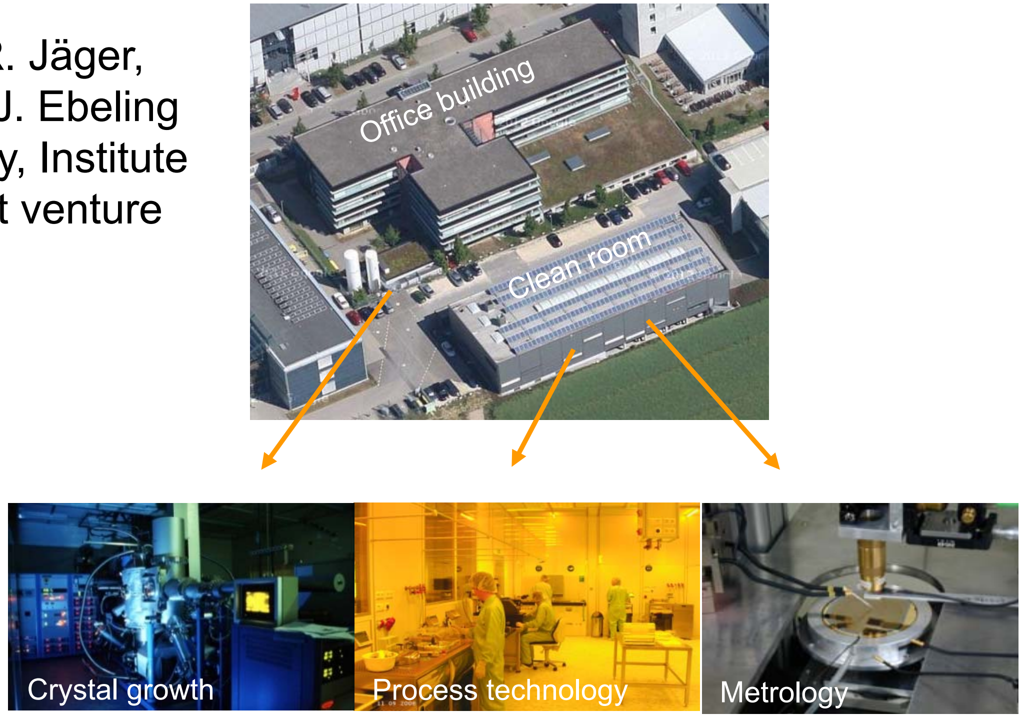
PHILIPS U-L-M photonics GmbH

U·L·M PHOTONICS

Brief company history

- 2000: Founded by M. Grabherr, R. Jäger, R. King, D. Wiedemann, K.J. Ebeling as start-up of Ulm University, Institute of Optoelectronics, in a joint venture with the company Schott
- 2005: Management Buy-Out
- 2006: Selling to Philips Lighting
- 2007: ISO 9001 certification
- 2008 Clean room (900 m^2)
- 2015 Employees ~160, ~ 250 Mio. VCSELs shipped in total
- 2016 Further expansion

Ulm site of the company



Facilities & Accommodation

2000	Foundation of U-L-M Photonics at Ulm University, Institute of Optoelectronics
2001	Start of production at Ulm University, renting lab space at adjacent Science Park Ulm (250m²)
2004	Renting additional space for administration and marketing at Science Park (170m²)
2007	Complete relocation of labs and offices to Science Park, expanding office space to 350m²
2008	Opening of laser factory (1800 m²), including clean room facilities (900 m²)
2013	Renting of additional 350m² office space in Science Park
2016	Property assigned for enlarging clean room facilities

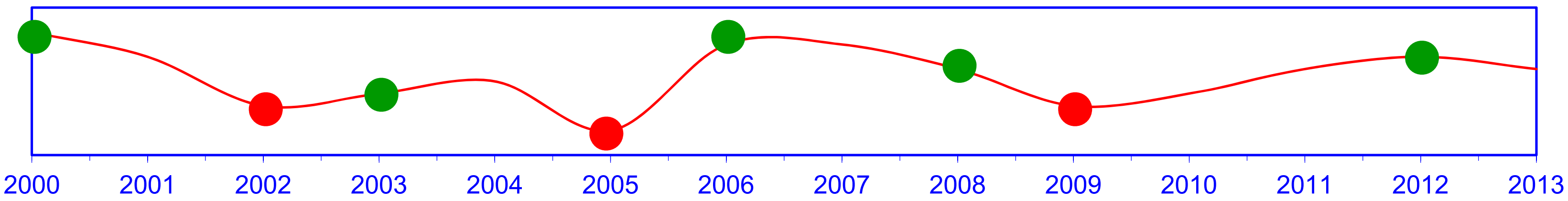

Ulm University, 2000


Lise-Meitner-Str 13, Science Park
Epitaxy, 2001


Lise-Meitner-Str 13, Science Park
Administration, Marketing
2004/2007/2013


Lise-Meitner-Str 17, Science Park
Laser Factory, 2008

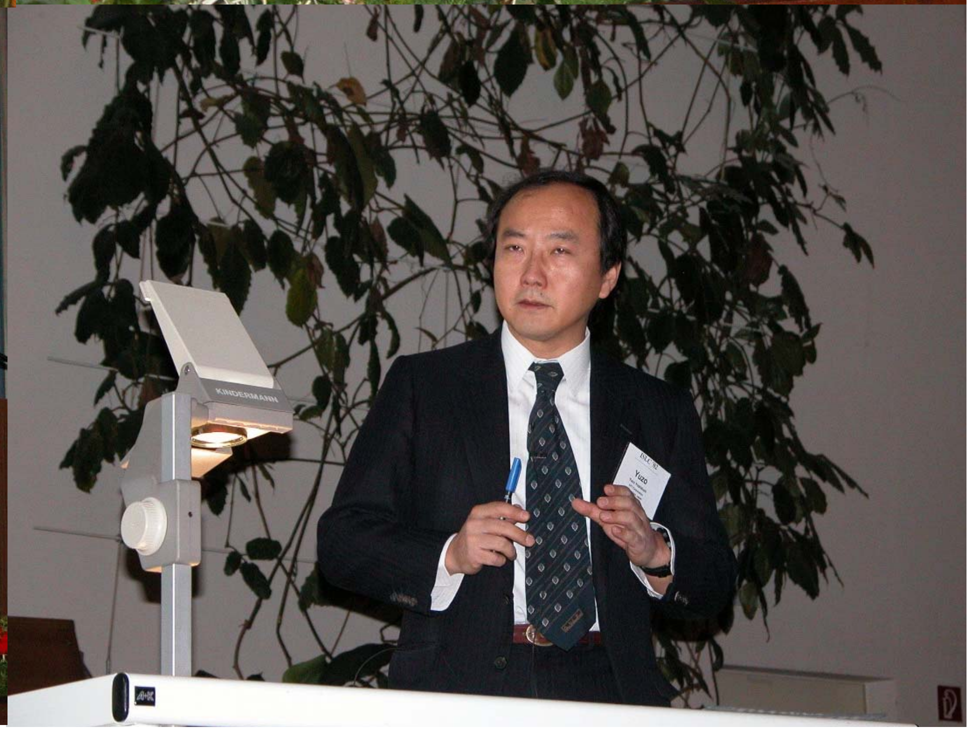
Company‘s Ups and Downs & Moods



1989- 2000	Technology development at Ulm University
2000	Foundation of the company U-L-M Photonics as a Joint Venture with SCHOTT → Investment phase **Business focus on data communication**
2002	Burst of IT bubble → Crisis phase
2003	Siemens becomes lead customer **Business focus on industrial sensors**
2005	Separation from SCHOTT (MBO) → Crisis phase Microsoft becomes lead customer **Business focus extended to laser computer mice**
2006	Philips becomes lead customer and acquires U-L-M Photonics → Investment phase **Business focus expanded to industrial illumination solutions**
2008	Start of production in new clean room
2009	Global financial crisis, Strategic realignment within Philips → Crisis phase **Data communication added to portfolio**
2012	Course for growth within Philips → Investment phase

ISLC 2002 Garmisch

ISLC 2002 Garmisch: Science



ISLC 2002 Garmisch: Culture

ISLC 2002 Garmisch: Social Event

ISLC 2002 Garmisch: Selection of Post Deadline Papers

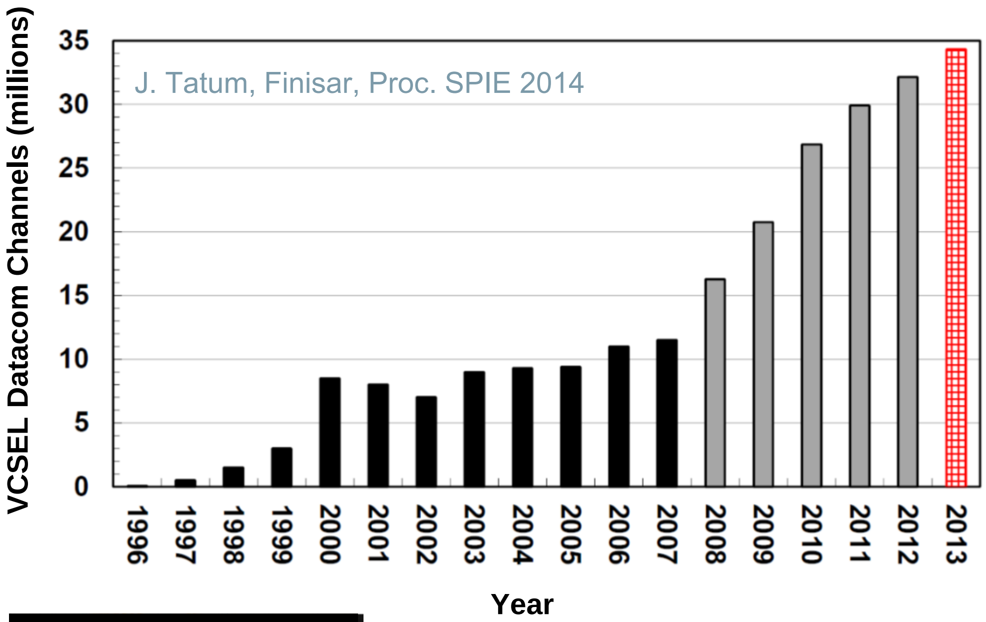
Addressed VCSEL Markets and Products

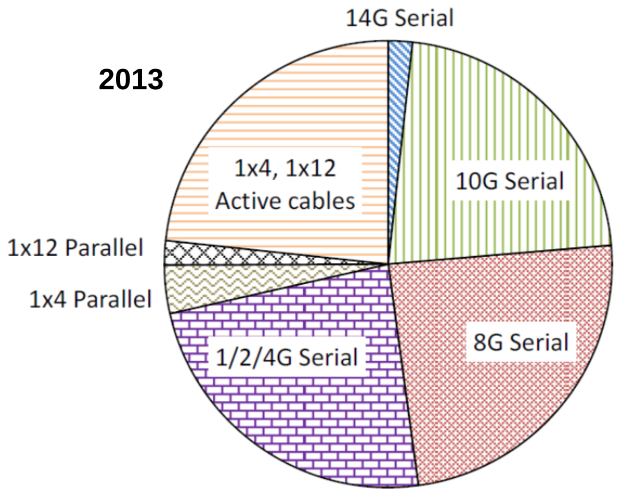
- **Optical data transmission**
  - Datacenters/Supercomputers
  - LAN/SAN
  - USB/Thunderbolt solutions

- **Consumer electronics**
  - Computer mice
  - Smartphones

- **Optical sensor and actors**
  - Semiconductor manufacturing
  - Industrial processing technologies

Datacom VCSELs Shipped and Applications





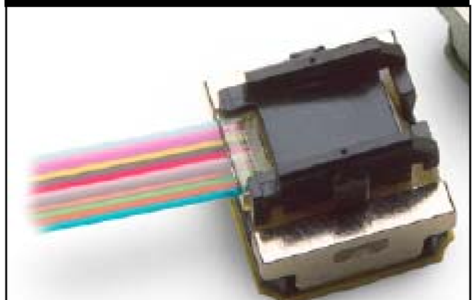
Optical Fibers

46 Tb/s Optical Backplane © 2011 IBM

Active Optical Cable

120 Gb/s 24 VCSELs

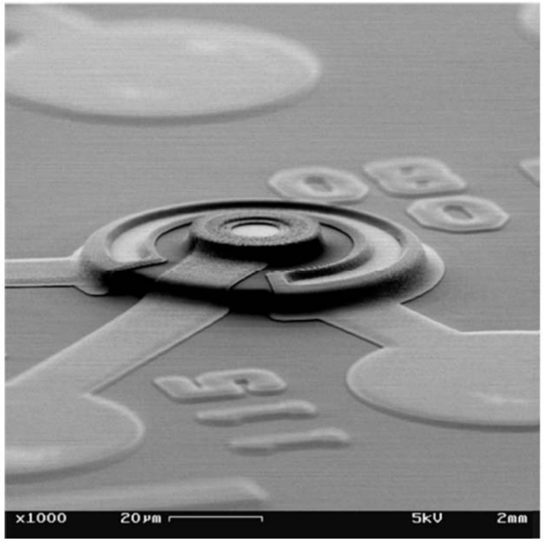
Optical Datacom Link



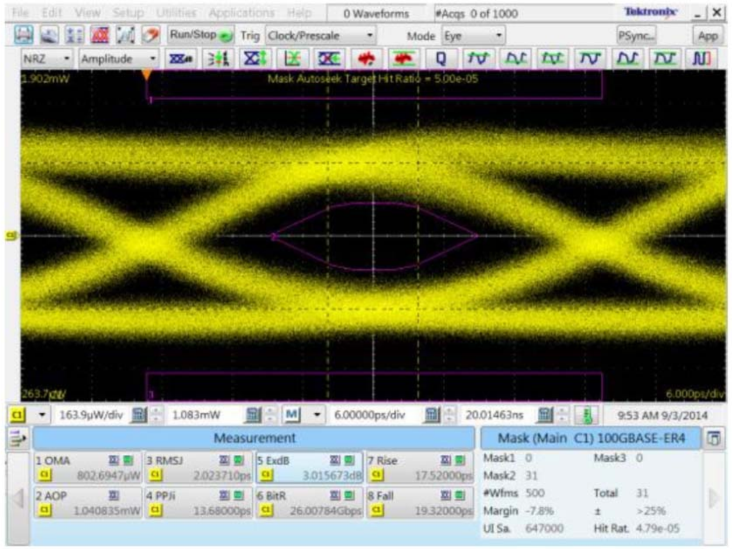
© 2011 Avago

Activities of Philips Photonics for Datacom

- Fabrication of VCSELs with single-mode or multi-mode emission, data rates up to 25 Gbit/s
- Single VCSELs and arrays with 4 or 12 laser diodes
- Fabrication of corresponding photodiodes and arrays
- Applications including transceivers, active optical cables, embedded optical modules and addressing standards like Infiniband, Ethernet, Fiber Channel and Thunderbolt
- Providing 8 Gbit/s 14 x 12 VCSEL and detector arrays for a routing demonstrator operating at 1.34 Tbit/s aggregate bandwidth

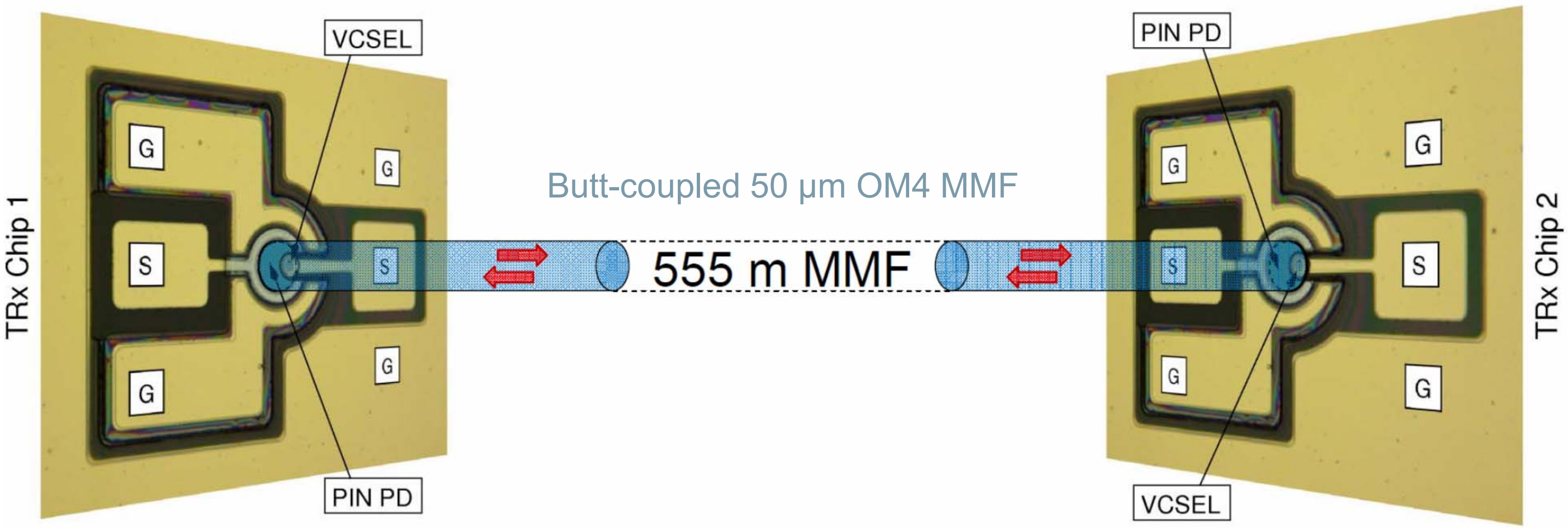


SEM photograph of a 25 Gbit/s VCSEL mesa structure

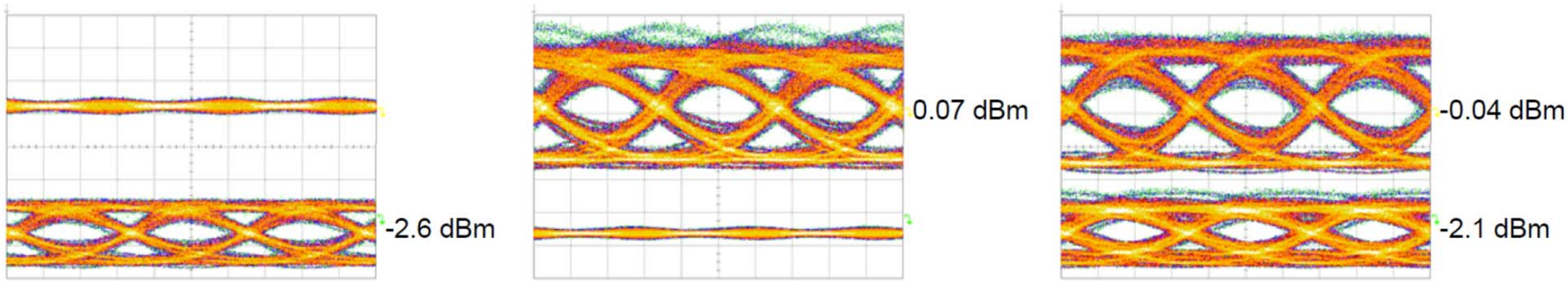


25 Gbit/s eye diagram of a 5 µm unstrained GaAs quantum well VCSEL at 6 mA current and 85 °C temperature and 3 dB extinction ratio

Bidirectional Data Transmission over 555 m High-Speed MMF

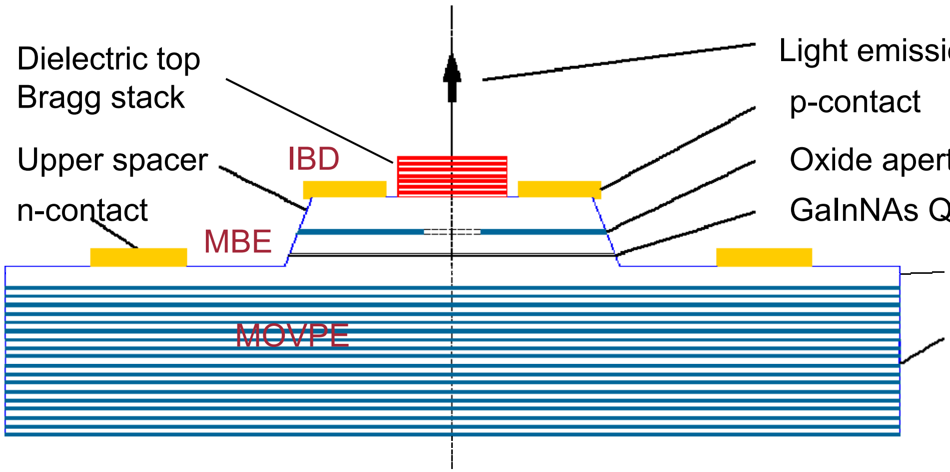


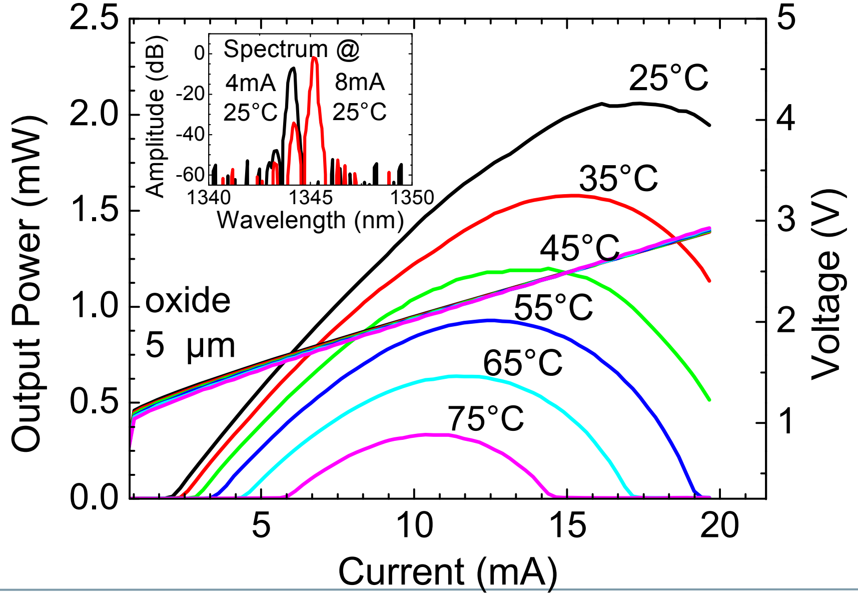
Half-duplex: Chip 1 → Chip 2	Half-duplex: Chip 1 ← Chip 2	Full-duplex: Chip 1 ↔ Chip 2



10.5 Gbit/s	10.5 Gbit/s	10 Gbit/s

Hybrid Type 1.345 µm Wavelength GaInNAs VCSEL





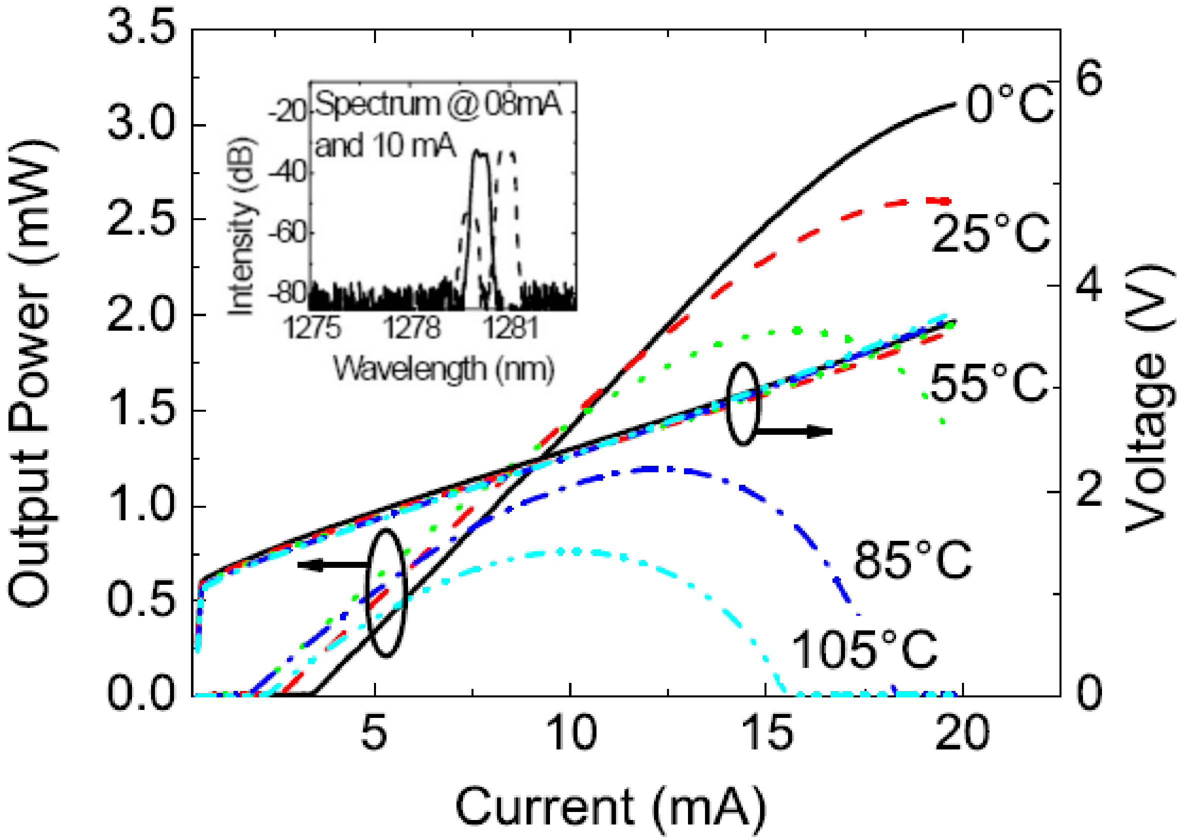
Features:

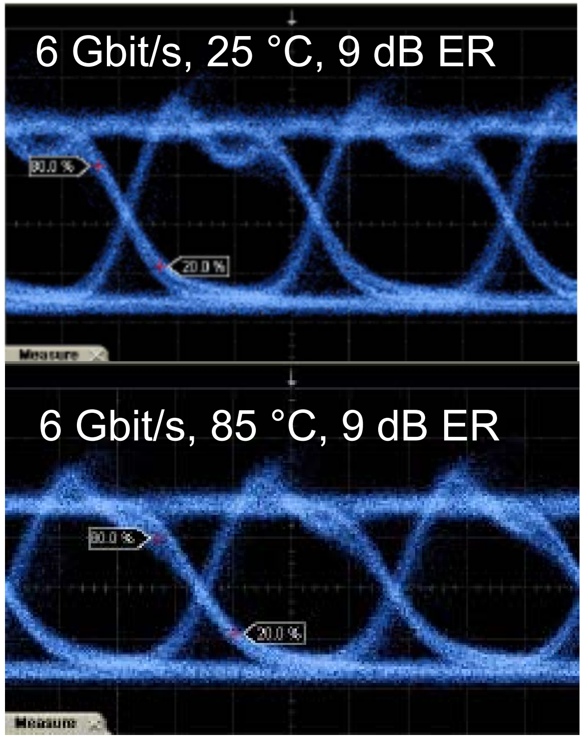
Modulation doped upper and lower spacer, un-doped bottom mirror, Al_2O_3-TiO_2 dielectric top mirror, intra-cavity contacts

Cooperation with

D. Supper, PhD Thesis, Ulm 2007

Data Transmission with 1.28 µm Wavelength GaInNAs VCSEL

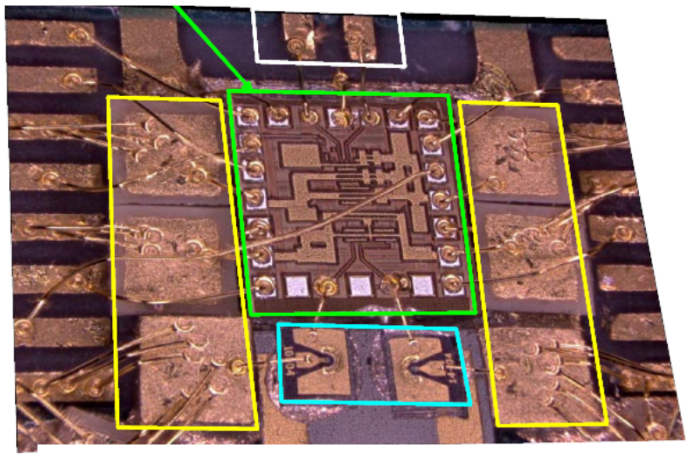


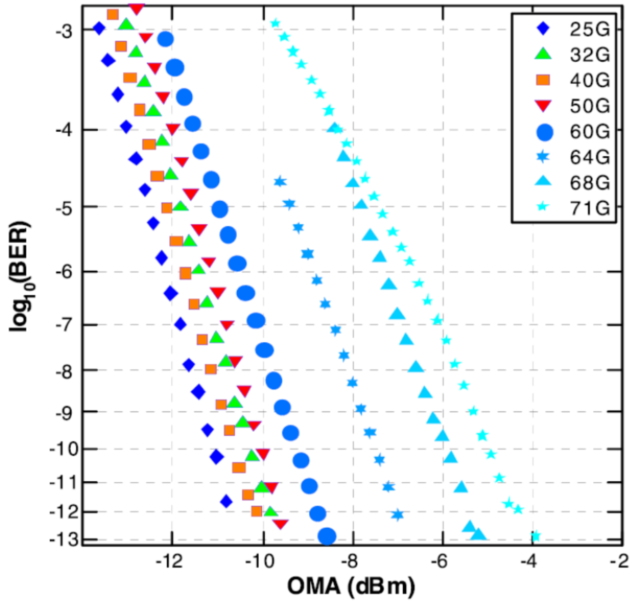


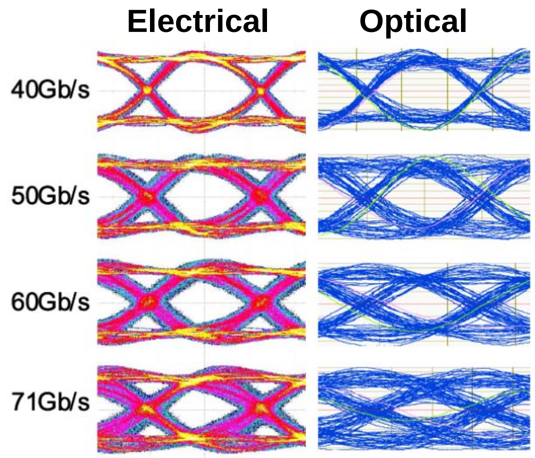
Properties:
Single-mode output power of 1.2 mW and 6 Gbit/s open eye with 9dB extinction ratio (ER) over a temperature range from 25 °C to 85 °C.

D. Supper, PhD Thesis, Ulm 2007

71 Gb/s NRZ Modulated VCSEL-Based Optical Link





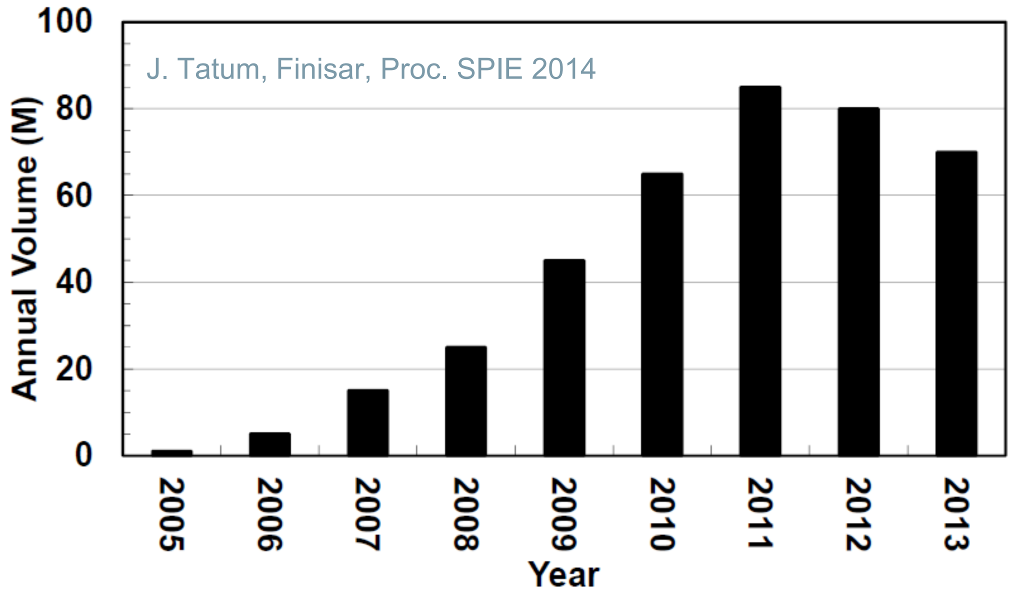


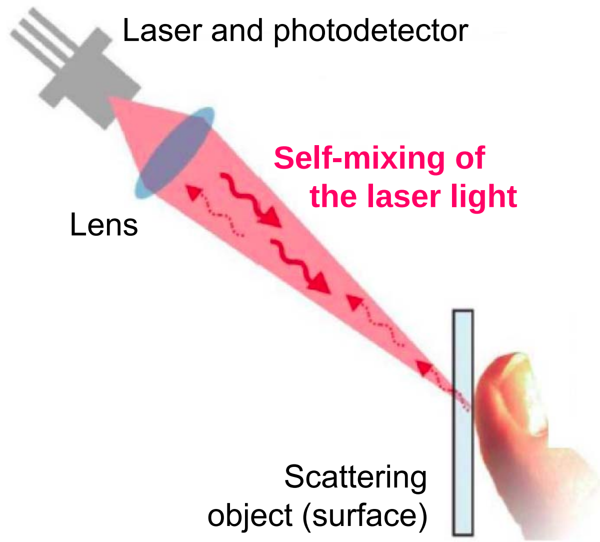
Remarks

- 850 nm VCSEL with 5 strained InGaAs QWs
- λ /2-cavity, feed-forward equalization
- Major contenders: IBM, Chalmers, Finisar, TU Berlin
- Avago announcement 2015: 1 million 25 Gbit/s systems shipped

D.M. Kuchta, A. Larsson et al., IEEE PTL, March 2015

Smart Sensor VCSELs Shipped and Applications

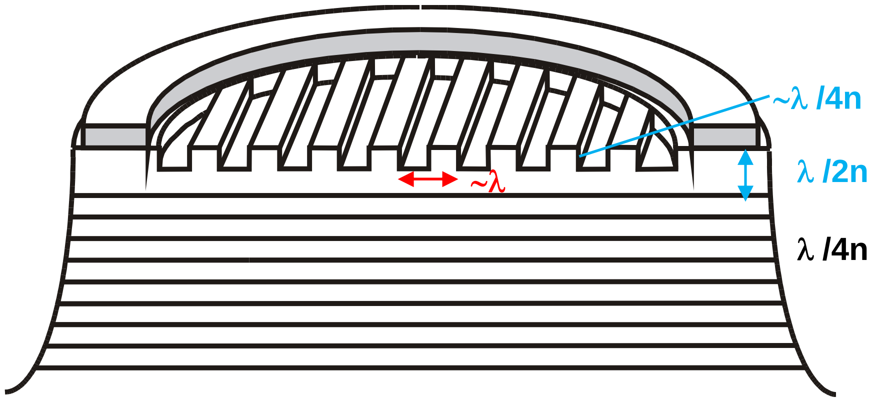


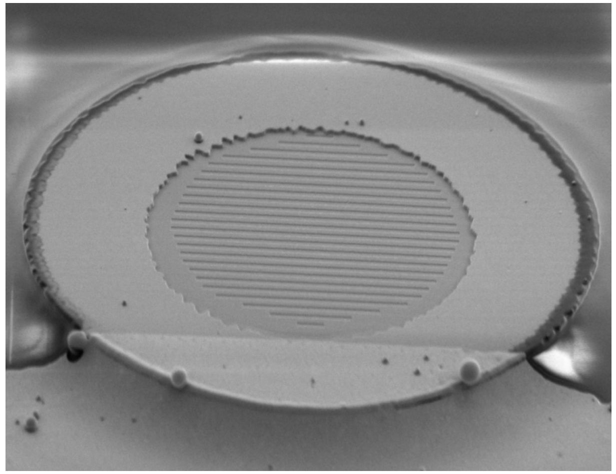


Computer Mice

A. Pruijmboom et al., Proc. SPIE 2008, Philips

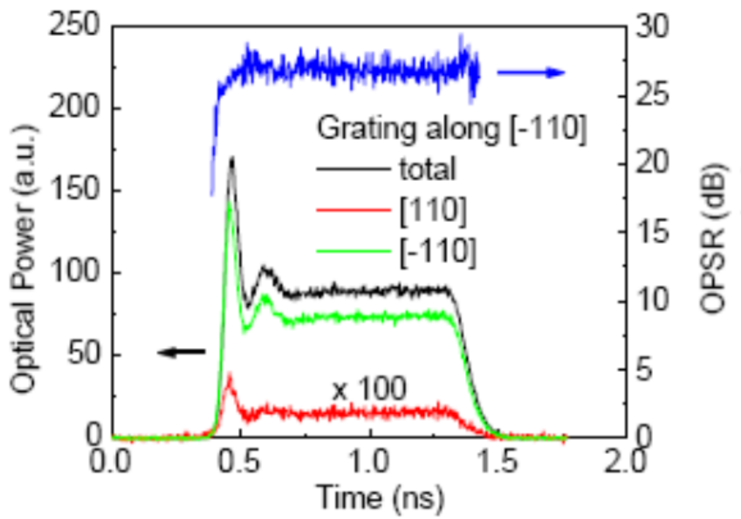
Reliable Polarization Control Using Inverted Surface Grating



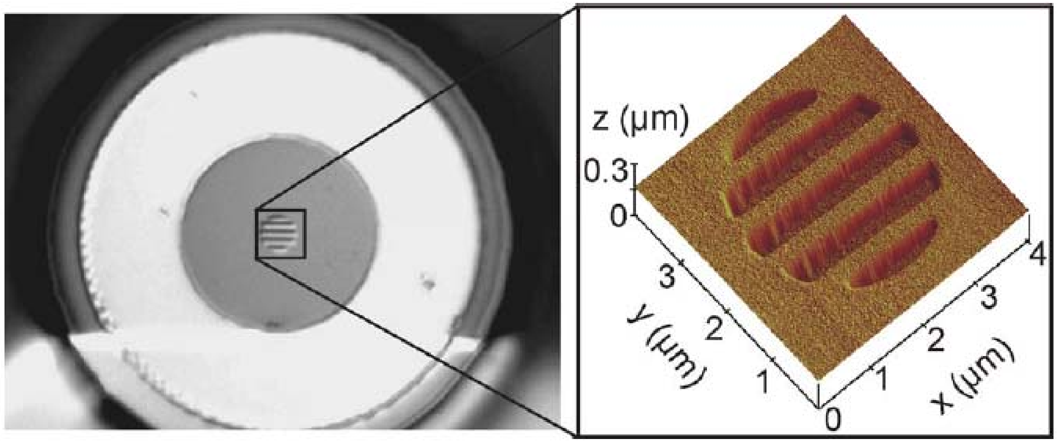


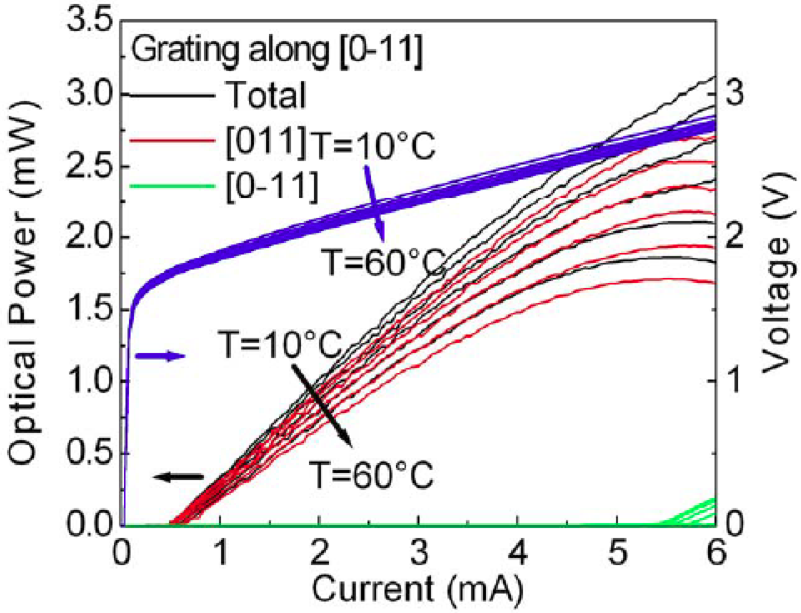
Method

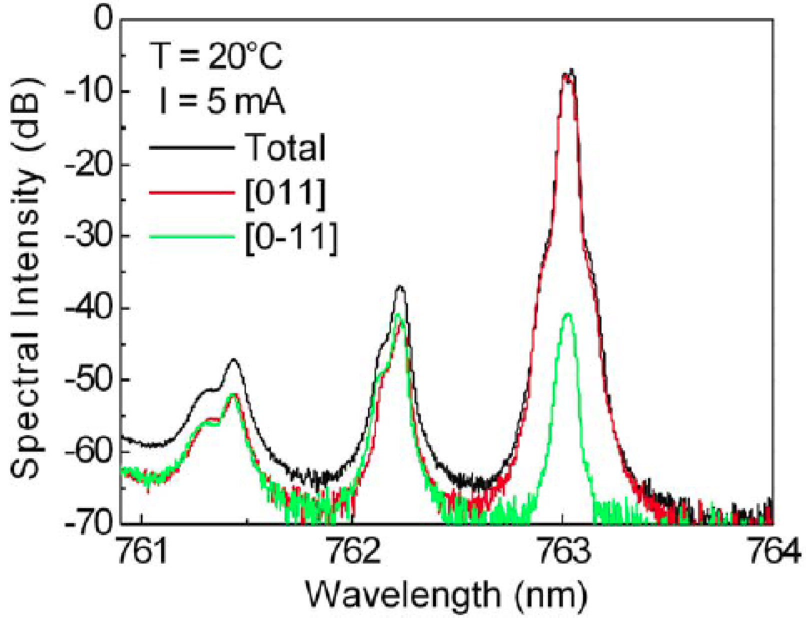
- Idea: Break symmetry by surface etched grating to overcome spurious internal birefringence
- Problem: Lasing threshold of polarization states is sensitively (often adversely) affected by lateral orientation and axial position of surface relief grating
- Solution: Etch **~λ/4n** deep "inverted" grating of period **~λ** and (110) orientation in topmost **λ/2n** thick layer
- Result: Stable linearly polarized emission in (-110) direction for fundamental and higher order transverse modes at negligible increase of laser threshold current
- High orthogonal polarization suppression ratio (OPSR) for cw and high-speed operation



Oxygen Sensing at 763 nm with Inverted Grating Relief VCSEL for e.g. Combustion Process Control







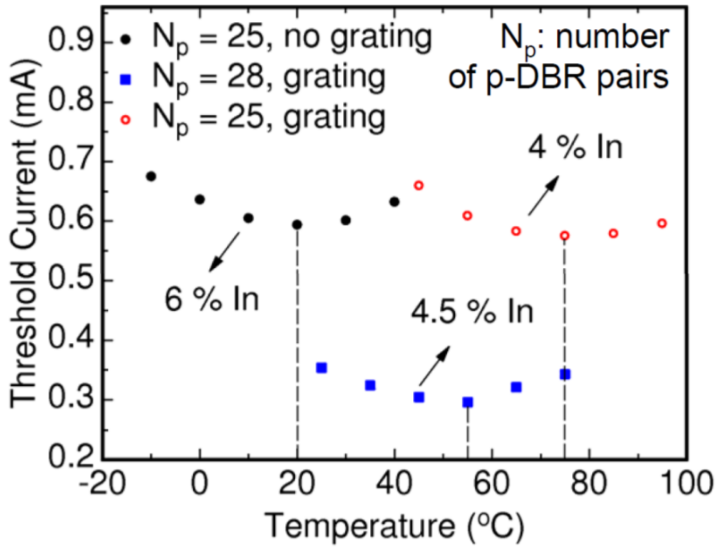
InGaAs QW VCSELs for Miniaturized Cesium Atomic Clocks

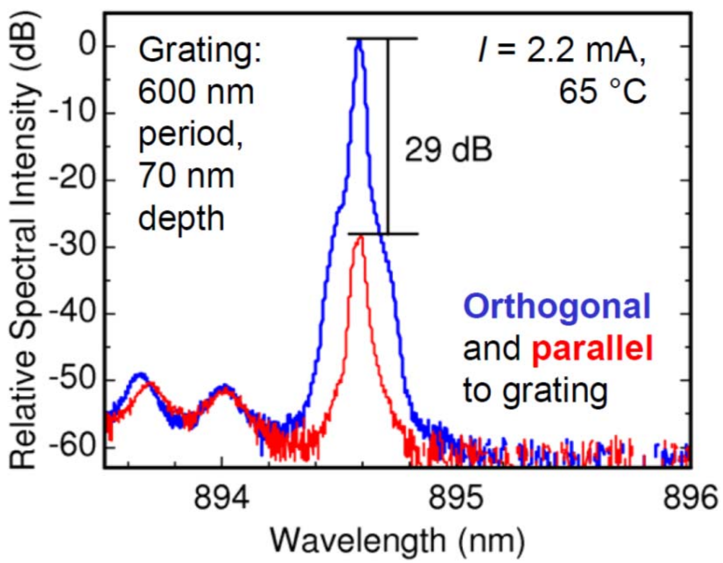
Requirements for Cs-based clock:

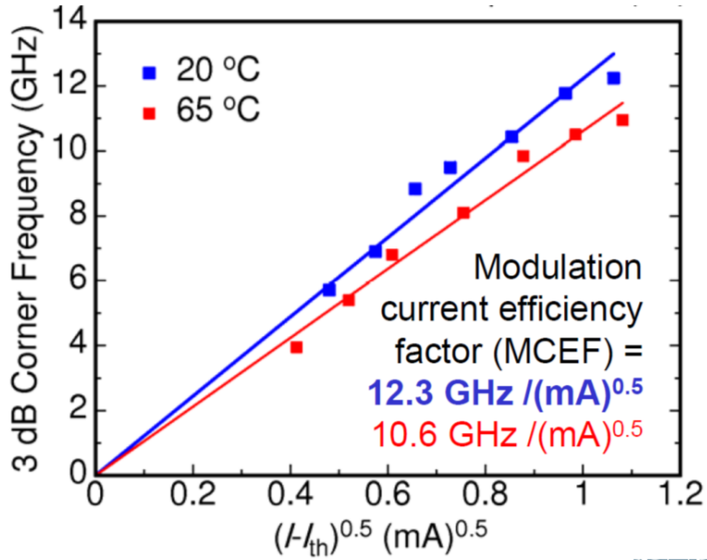
- Wavelength of 894.6 nm (D1 line), P = 100 µW
- Single transverse and polarization mode
- 3 dB modulation bandwidth > 5 GHz
- Low power consumption
- Low intensity noise, narrow linewidth

Alternatives: 780.2 nm (Rb D2), 795.0(Rb D1), 852.4 (Cs D2)

Potential: attractive niche market for ~100000 pieces per year





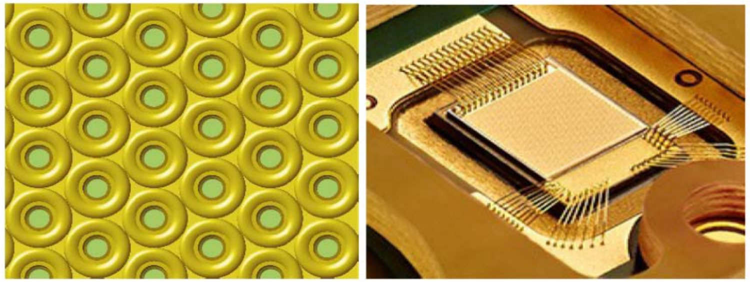


A. Al-Samaneh, R. Michalzik et al., IEEE PTL 2011

High-Power VCSELs: Increasing Interests

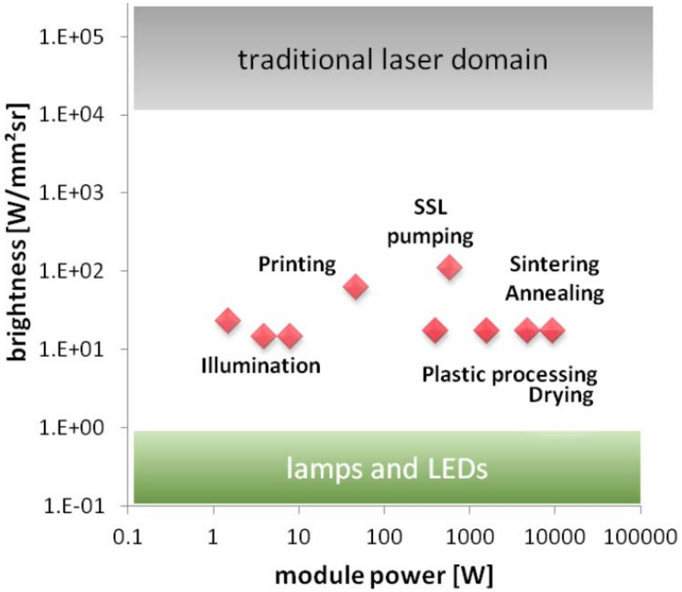
Technology and Characteristics:

- Approach: Combine 100's, 1000's, or even 10000's low-power elements in large 2-D arrays (cm-scale)
- Advantages similar to low-power VCSELs: low-cost automated manufacturing with wafer-scale processing and testing, high reliability (no COD) and high temperature operation, low-divergence circular output beam and narrow spectrum
- Current performance levels: PCE > 40 % (800 to 1100 nm wavelength range), Output power from few Watts to ~1 kW from single chip, Power density ~ 1 kW/cm² (cw) & ~ 4 kW/cm² (quasi-cw), Brightness up to ~ 10 MW/(cm² sr) from single chip (30 W)



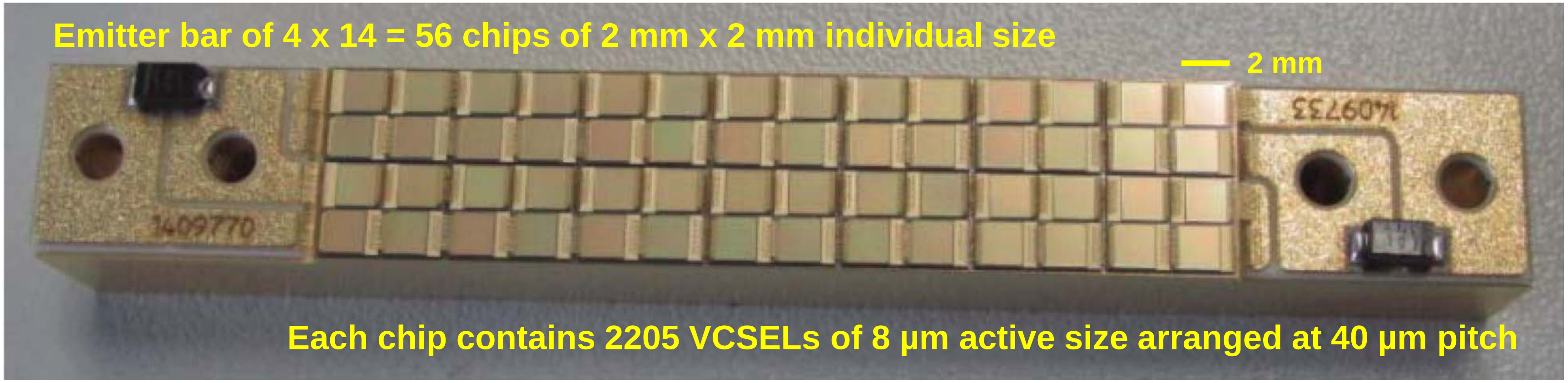
8 µm VCSEL array of 40 µm pitch and assembled chip with more than 2000 individual lasers

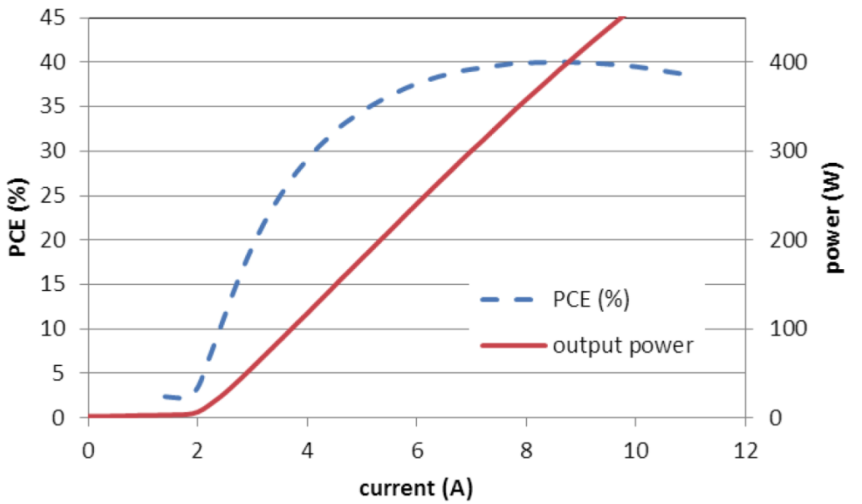
Applications:



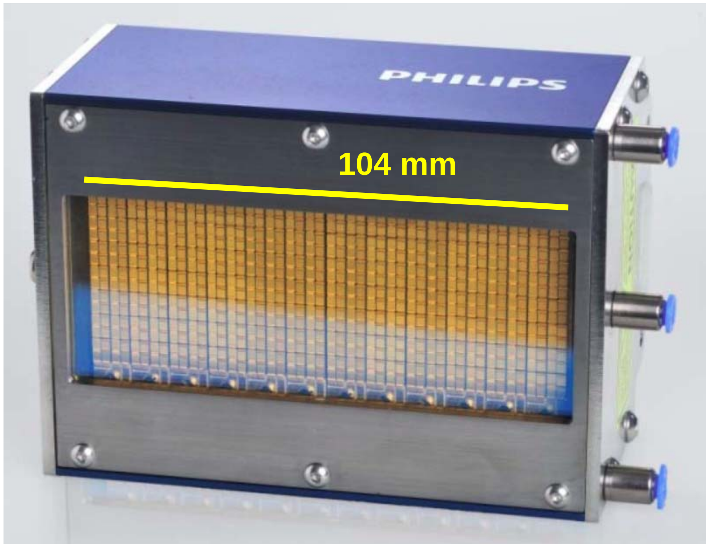
H. Moench et al., Proc. SPIE 2015

4.8 kW High Power VCSEL Array Module at 808 nm



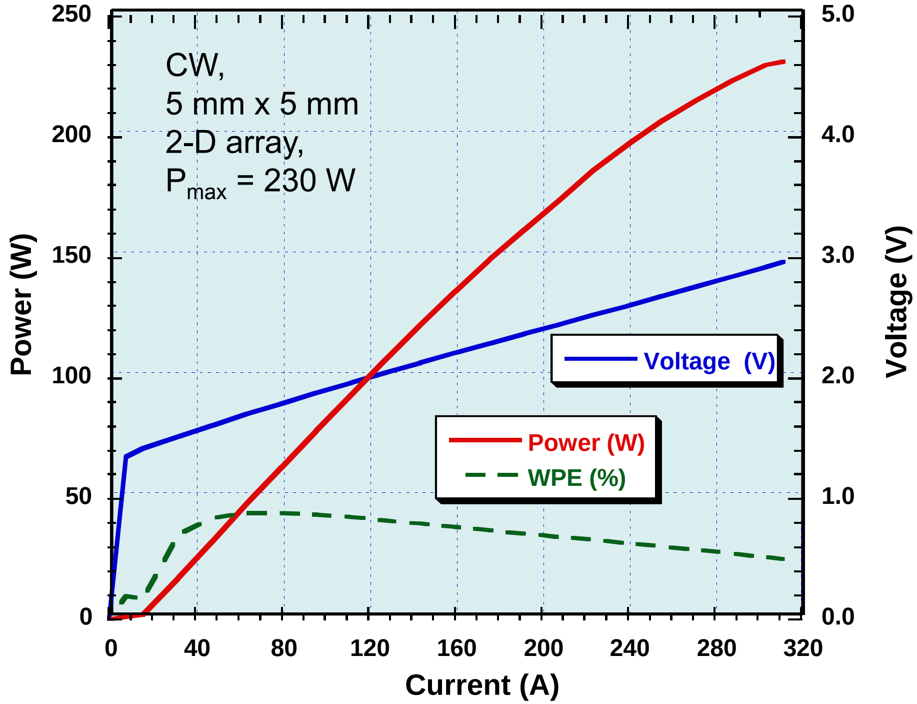


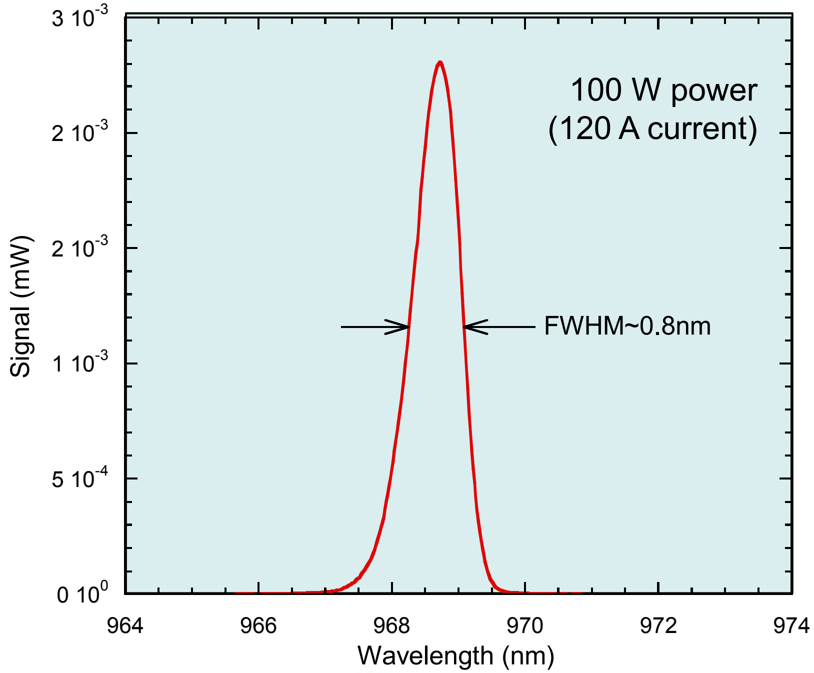
Output power and efficiency of bar with 56 chips

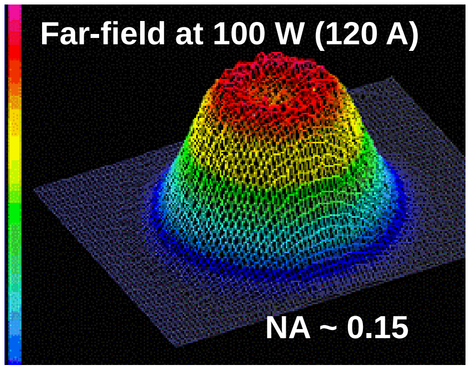


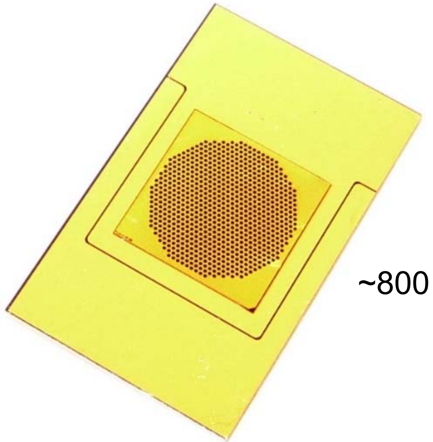
2-D VCSEL array module with 4.8 kW output power

High-Power VCSEL Array



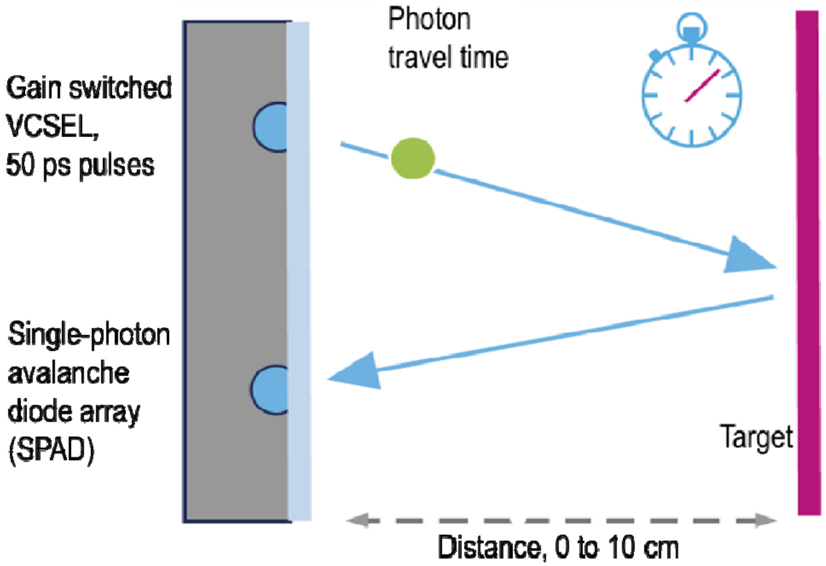


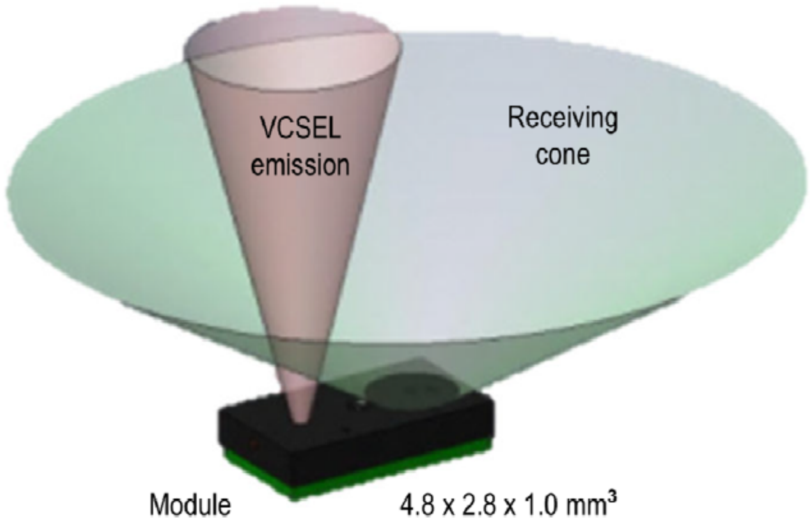




~800 VCSELs

VCSEL-Based Time-of-Flight Sensor: Future Mass Market?





Features:

- Fully integrated module: VCSEL emitter and SPAD array detector
- Low power consumption
- Absolute distance measurement, independent of target reflectance
- Accuracy depending on number of averaged samples

Applications:

- Proximity detection for smart phones, in particular for turning off display illumination
- 1-D gesture control
- Collision avoidance for cleaning and cutting robots
- Liquid level monitoring
- Human-machine interface

Source: STMicroelectronics

Fast VCSEL-Based Autofocus System in LG Smartphone Cameras

Adjusts focus by measuring distance to subject using a laser, allowing faster focus speed even in low-light situations.

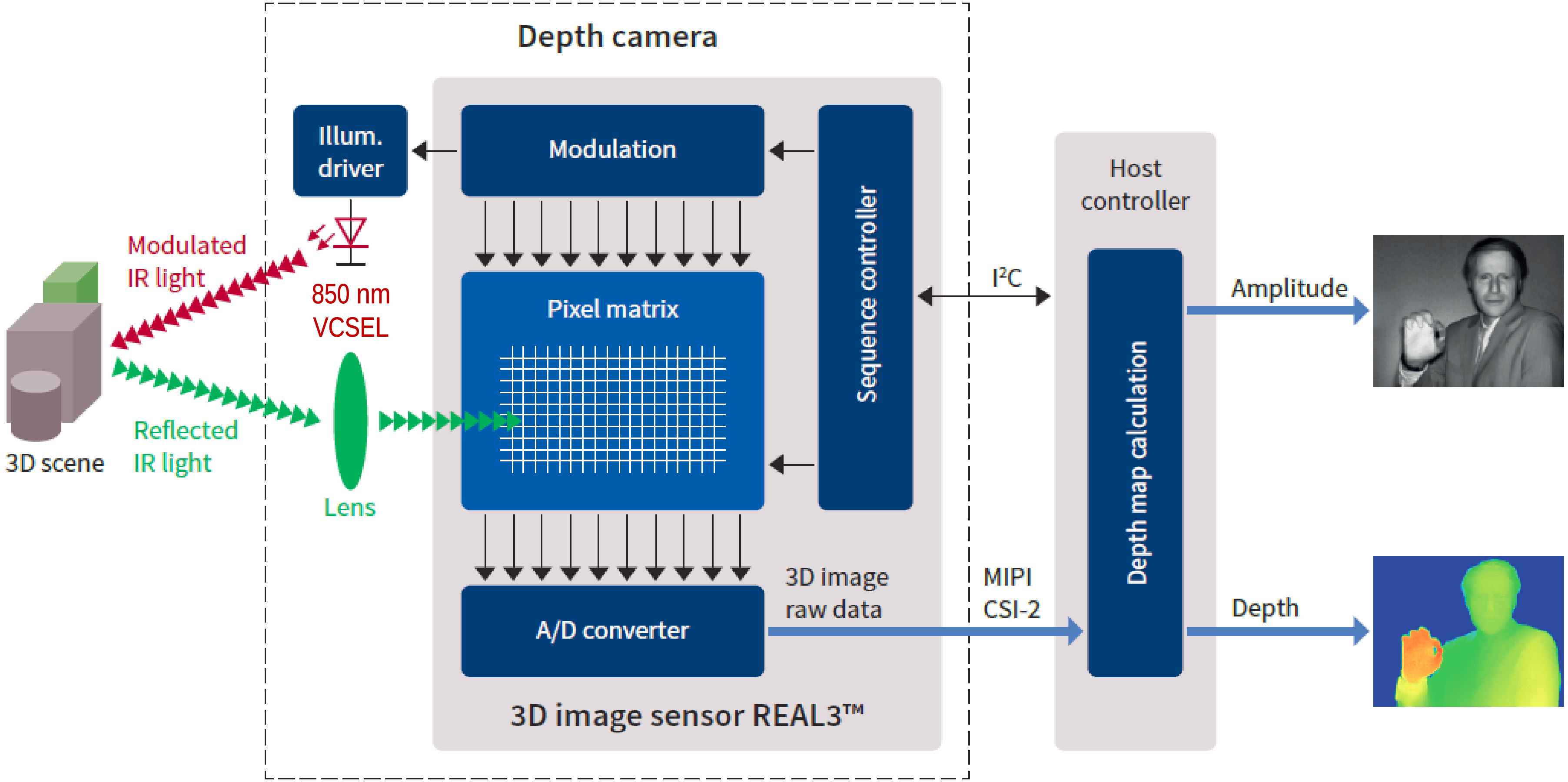
OIS+ LASER AF

D851 model shown in Metallic Black

Dramatization

www.lg.com/us/cell-phones/lg-D851-Metallic-Black-g3

3-D Photography and Video with VCSEL and PMD Camera: Potential Future Mass Market for VCSELs?



Photon Mixer Device (PMD) Technology:

- 100 MHz VCSEL and pixel matrix modulation
- 352 x 288 pixels with micro-lenses, 0.1-4m distance
- ~300 mW power consumption of VCSEL & sensor

Applications:

- Gesture recognition, augmented reality
- 3-D object profiling, definition of security zones
- Surveillance, indoor navigation, autonomous driving

Source: Infineon 2016

Lenovo Phab 2 Pro: VCSEL Based 3-D Video and Photography

Features:

Lenovo Phab 2 Pro allows for depth sensing and motion tracking and provides 3-D rendering of the scene. It includes Tango - a new technology from Google that enables augmented reality (AR) gaming and utilities where you can see objects and information overlaid onto the real world. Moreover, with the 3-D capability you can precisely determine measures of objects with just the phone or visualize furniture like a new table or sofa to see how it looks in your home.

shop.lenovo.com/us/en/tango/index.html

What's New with Project Tango - Google IO 2016

Statement Kenichi Iga, Bower Award 2013

Statement Kenichi Iga, Bower Award 2013

ISLC 2016: Happy 50th Anniversary!

Thanks to R. Michalzik and M. Grabherr for their support!