27th International Semiconductor Laser Conf. 2016

Since 1881

VCSEL Odyssey ++

2016.9.12 Kobe

Kenichi Iga

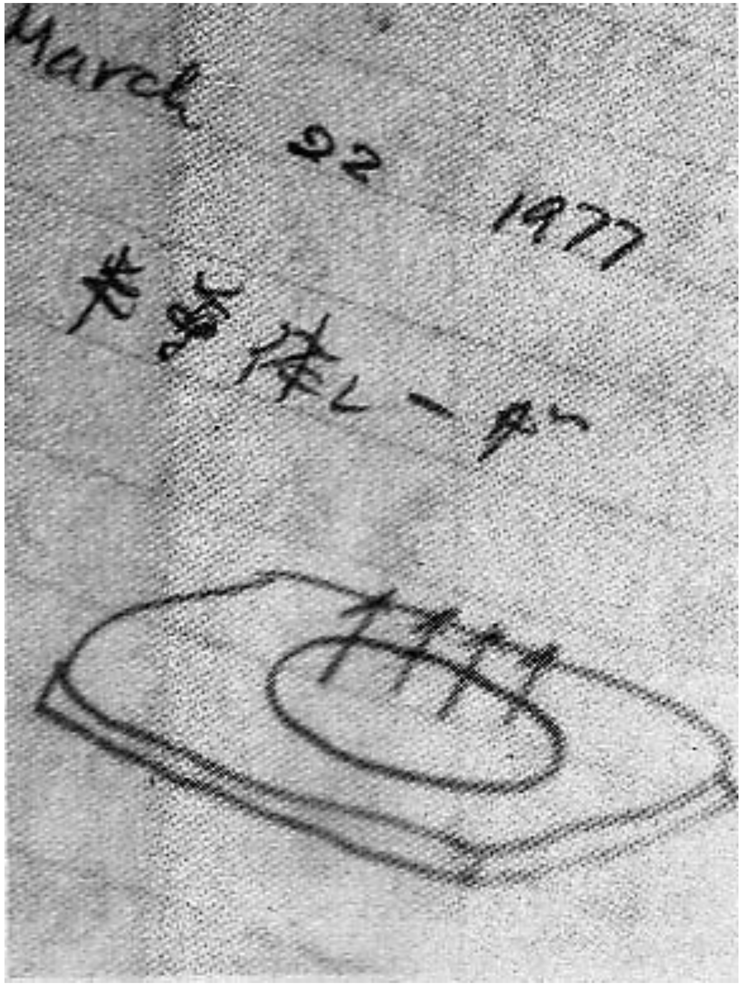
Tokyo Institute of Technology
Professor Emeritus
/Former President

Logo: Microoptics Conference 2013
at Tokyo Institute of Technology http//:www.comemoc.com/

Franklin Medal/ Bower Prize

2013.4.25 at Franklin Museum, from President Wint

Initial Idea 1977.03.22



The First Presentation, March 1978

K. Iga, T. Kambayashi, and C. Kitahara:

The 25th Spring Meeting of Applied Physics Societies 27p-C-11 (1978) 63.

GaInAsP/InP Surface Emitting Laser (I)

K. Iga, T. Kambayashi, and C. Kitahara

The demand for semiconductor lasers operating in single-mode and emitting a sharp beam is strongly recognized. For the purpose of solving this problem, we aim at the development of a surface emitting laser. As a initial stage, this study suggests a device idea as shown in Fig. 1 and presents a necessary etching technology. Also we confirmed the LED structure as a preliminary experiment for realization.

The surface emitting laser structure is consists of p-electrode and etched surface of substrate as has been shown in Fig. 1 and the light is taken from the etched well. From theoretical estimation, it is led that the reflectivities r_1 and r_2 for two mirrors should be >0.97 assumed that cavity length L=10mm, active layer thickness L_1=2mm, optical loss a=10cm^{-1}, and optical gain g=200cm^{-1}, respectively.

We grew the $Ga_{0.2}In_{0.8}As_{0.46}P_{0.54}$/InP wafer by a vertical LPE system. We formed a p-electrode of 50mm on the epi-side and etched a hole of 100mm in diam and 25mm in depth. We have used a so-called KKI etch consisting of HCl:CH_3COOH:H_2O_2=1:2:1 having a relatively large etching rate after a lot of trials. The etching rate is 1mm/min and there was no problem in the damage of photoresist OFPR. The photograph of etched surface is shown in Fig. 2 which shows a mirror surface. We observed a near field pattern under pulsed condition as shown in Fig. 3. We are going to improve the epitaxy and etched condition to realize a surface emitting laser together with the innovation of reflectors/electrode.

１９７８年（昭和53年）春季 第２５回 応用物理学関係連合講演会
とき：昭和53年３月27日(月)～３月30日(木)
ところ：武蔵工業大学 TEL(703)3111
（〒158 世田谷区玉堤１－28－１）

27p—C—11　面発光形 GaInAsP/InP レーザ (I)

東工大・精研　伊賀健一，上林利生，°北原知之

光通信，光電子機器等の用途に対し指向性が鋭く，単一モードで発振するレーザへの要求が高い。本研究では，1μm帯で発光するGaInAsPを用いて，この問題点を解決できるレーザとして面発光形短共振器半導体レーザの開発を目指す。今回，構成法の検討と加工に不可欠な化学エッチング法の開発を行い，一段階として図1に示すような構造のダイオード素子を試作し，発光を確認した。

レーザ構造は，図1に示すようにP側電極とn側基板を深くエッチしエッチ底面を反射鏡とするもので，エッチング面から光を放射する。いま共振器長L=10μm，活性層厚L_1=2μm，光損失α=10cm^{-1}，活性層利得g=200cm^{-1}とするとレーザ発振するのに必要な反射鏡の反射率r_1,r_2はr_1=r_2=0.97となる。

製作に当っては，縦形LPE炉により成長させた$Ga_{0.2}In_{0.8}As_{0.46}P_{0.54}$/InPウエハ[1]の両面に電極後，フォトレジストでパターンを作り，基板側に100μmφ深さ25μmの円形の穴，P側に50μmφの電極を化学エッチングにより作り図1に示す構造に加工した。GaInAsP/InP半導体加工用化学エッチング液として種々の組成のエッチング液を試した[2]がここでは比較的エッチ速度の速い，HCl:CH_3COOH:H_2O_2=1:2:1の組成のものを用いた。エッチ速度は約1μm/min(~20℃)であるがエッチの方法により多少変化する。またこのエッチ液に対するフォトレジスト(OFPR-II)の耐性もほとんど問題ない。加工したウエハのn側InP基板を図2に示す。図のようにエッチ底面が非常によい鏡面状態のものが得られる。このウエハにパルス電流を注入して図3に示すような発光を確認した。今後さらにエッチング加工を改善するとともにウエハ構造，電極構造について検討を加え，面発光形レーザの製作を行う予定である。

なお本研究の一部に文部省科研費（特定，光導波）の補助を得た。

参考文献　1) K.Wakao, K.Moriki, T.Kambayashi and K.Iga JJAP, 16, (1977) 2073
2) 上林，北原，伊賀，昭和53年電子通信学会全国大会予稿

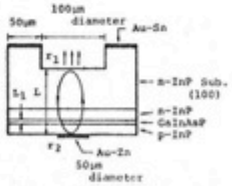


図1. 面発光形レーザ

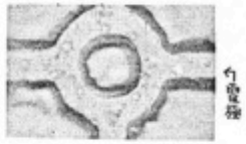
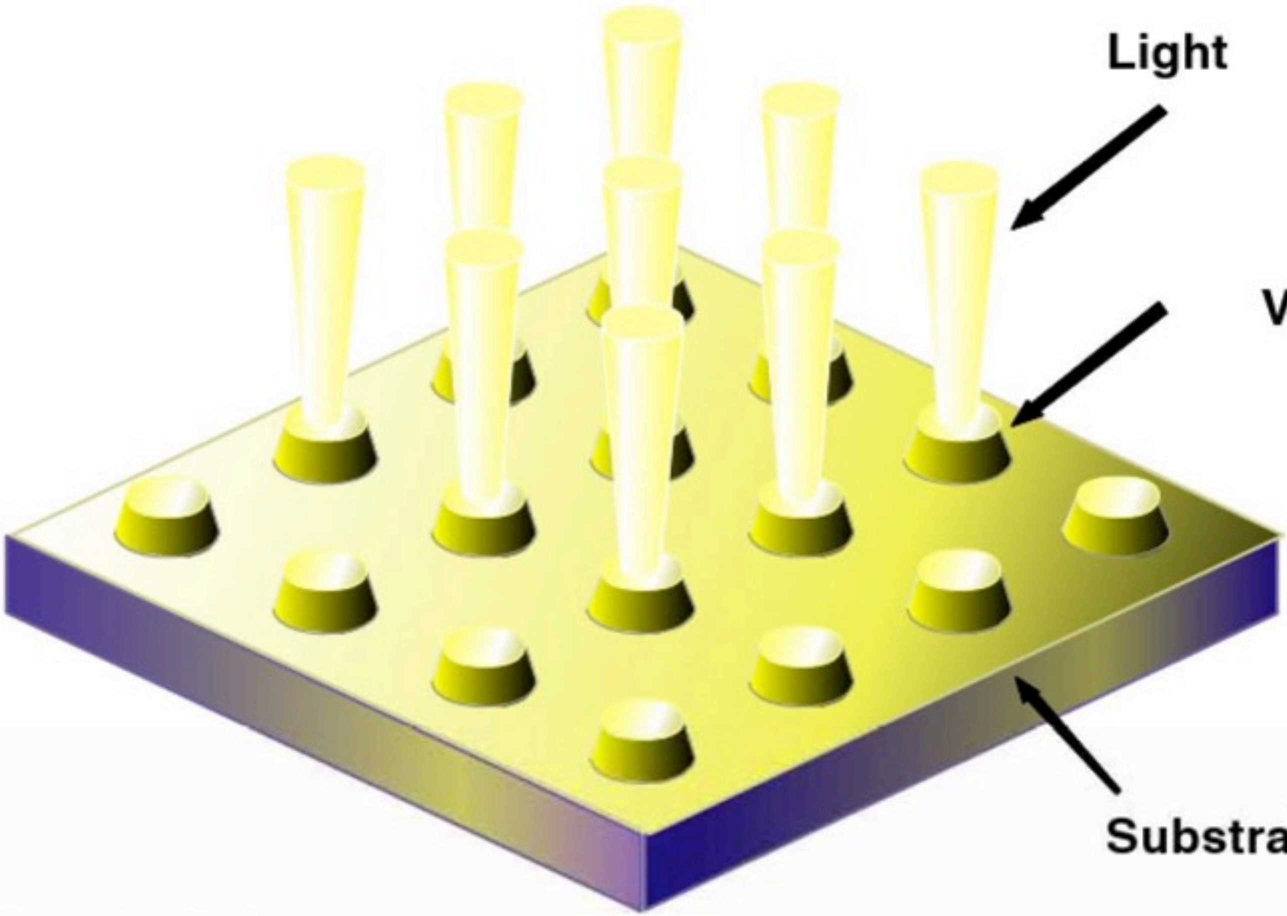


図2. 試料の基板側パターン

図3. 基板側の発光パターン

＋LED Symposium 1978.10

Vertical Cavity Surface Emitting Laser



8-10 September 2003

By K. Iga 1977

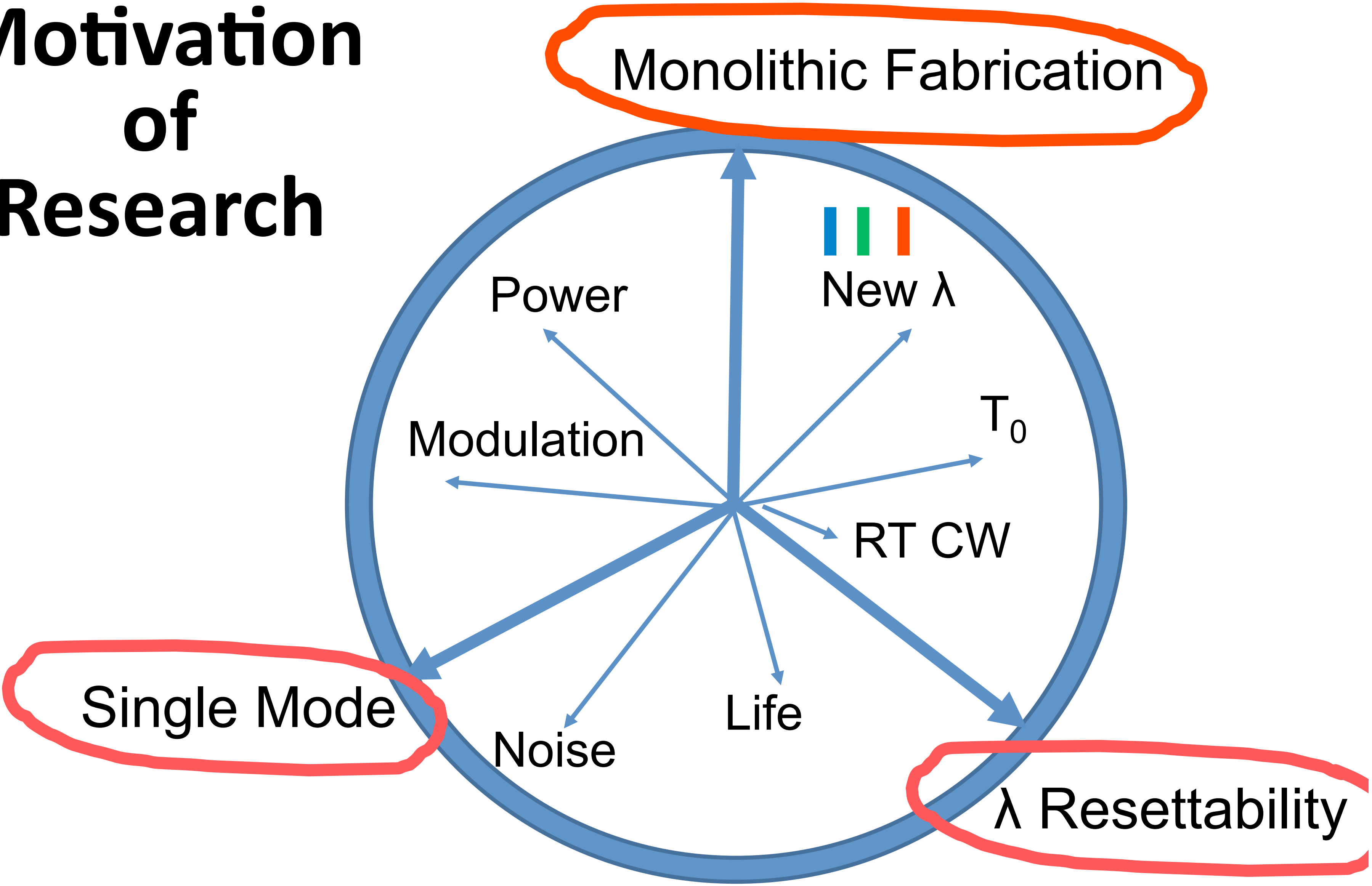
Three Verticals in 1977

1977 Vertical Cavity Surface Emitting Laser
By Kenichi Iga

1977 Vertical Magnetic Memory
By Shunichi Iwasaki

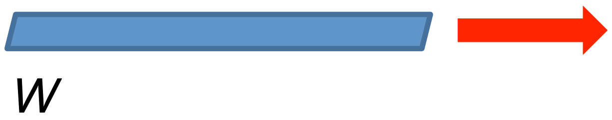
1977 VAD: Vapor-phase Axial Deposition (Fiber)
By Tatsuo Izawa

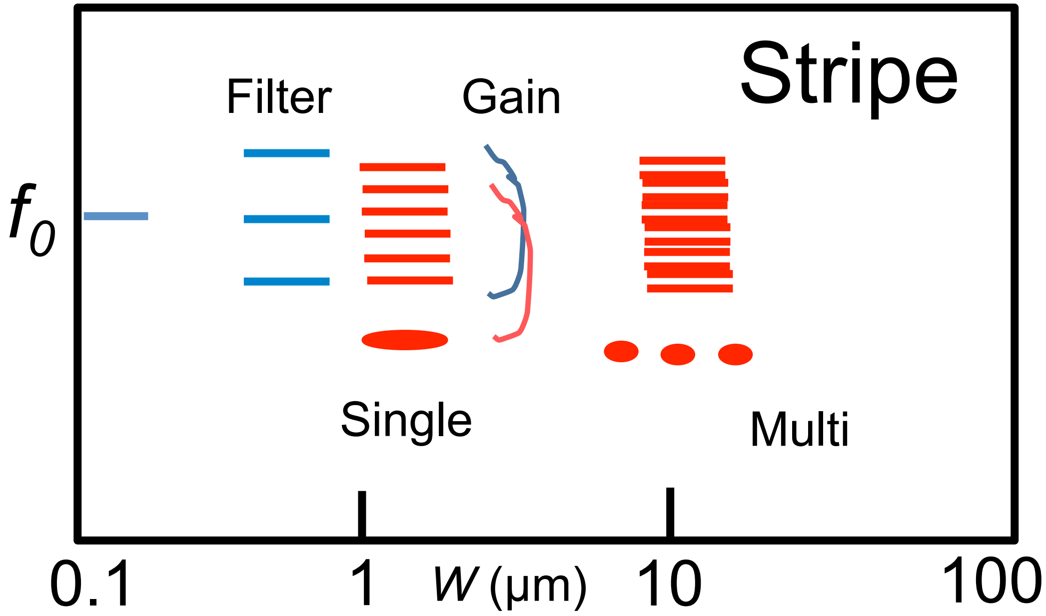
Motivation of Research



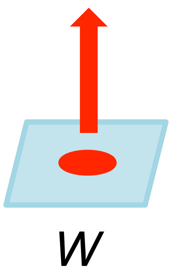
VCSEL Motivation

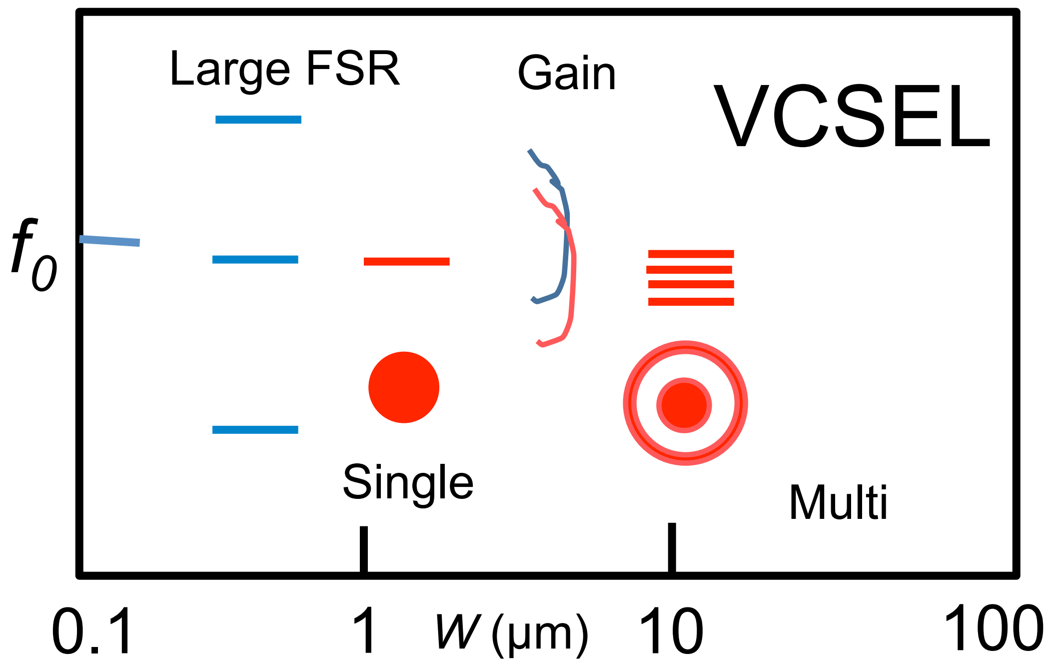
Requirement Not Demand	Etched -Mirror	DFB	VCSEL
1. Monolithic Fabrication	Yes	Yes (Facet-Needed)	Yes
2. Single Mode	<50μm	Phase-Shifter	Yes
3. Wavelength: Reproducibility	No	Yes	Yes (Technology Depend)





Stripe
vs.
VCSEL

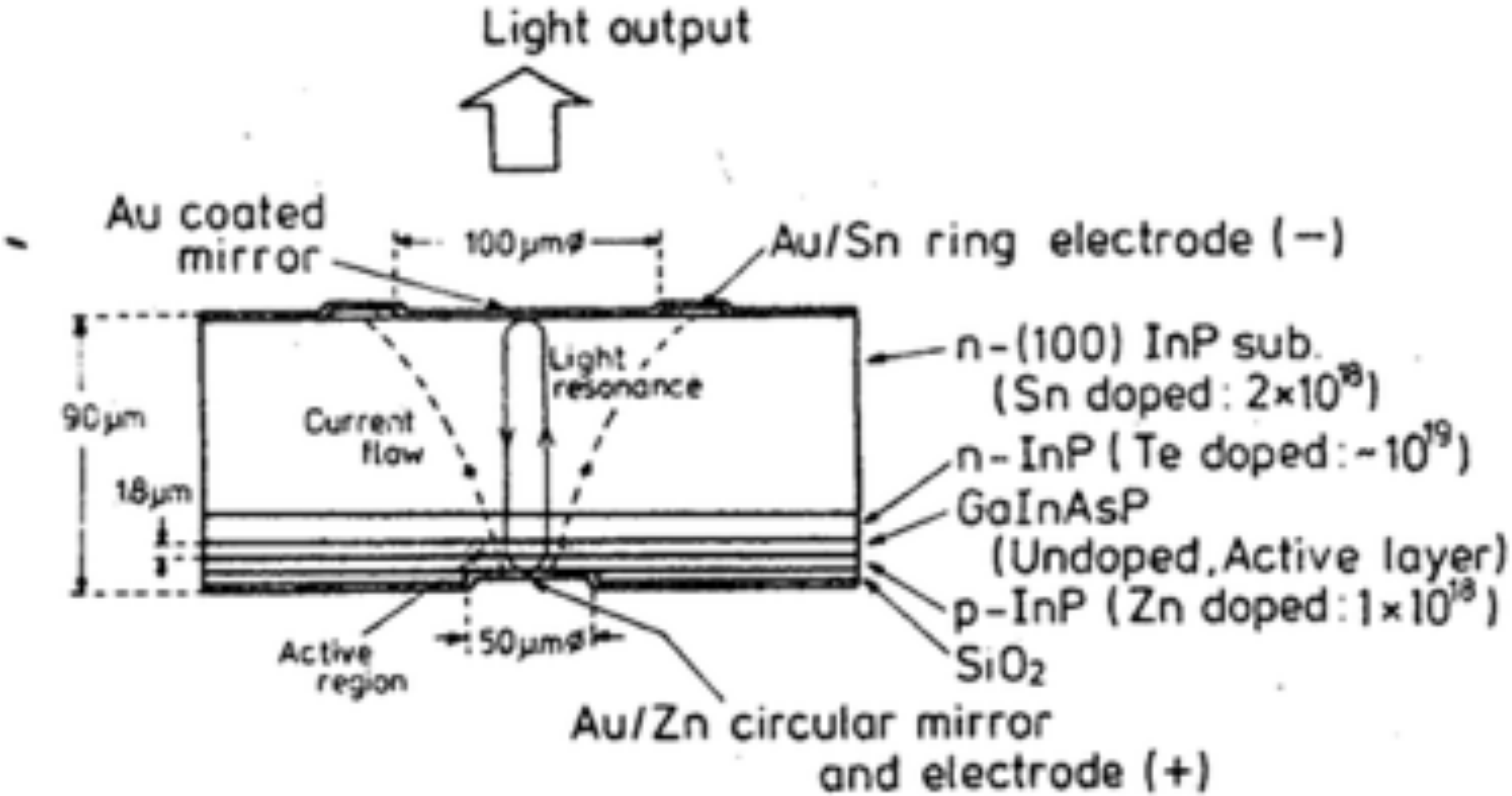




VCSEL Research and Development

1977 "Surface Emitting Laser" - Conception
1978 First report
1979 First demonstration
1982 6-micron cavity: Clear VCSEL-mode achieved
1986 Buried heterostructure, I_{th}=6mA
1988 First room temperature CW λ=820nm
1989 mA-I_{th} demonstrated
1993 First room temperature CW λ=1,300nm
1995 Low threshold laser demonstrated I_{th}<0.1mA
1998 Room temperature CW λ=1,500nm
1999 VCSELs opened Gigabit LAN market
2001 High-end fiber-optics system & 10 Gigabit LAN
Laser printer, Optical mouse, …
2011 Toward wide areas in VCSEL photonics
2022 ?

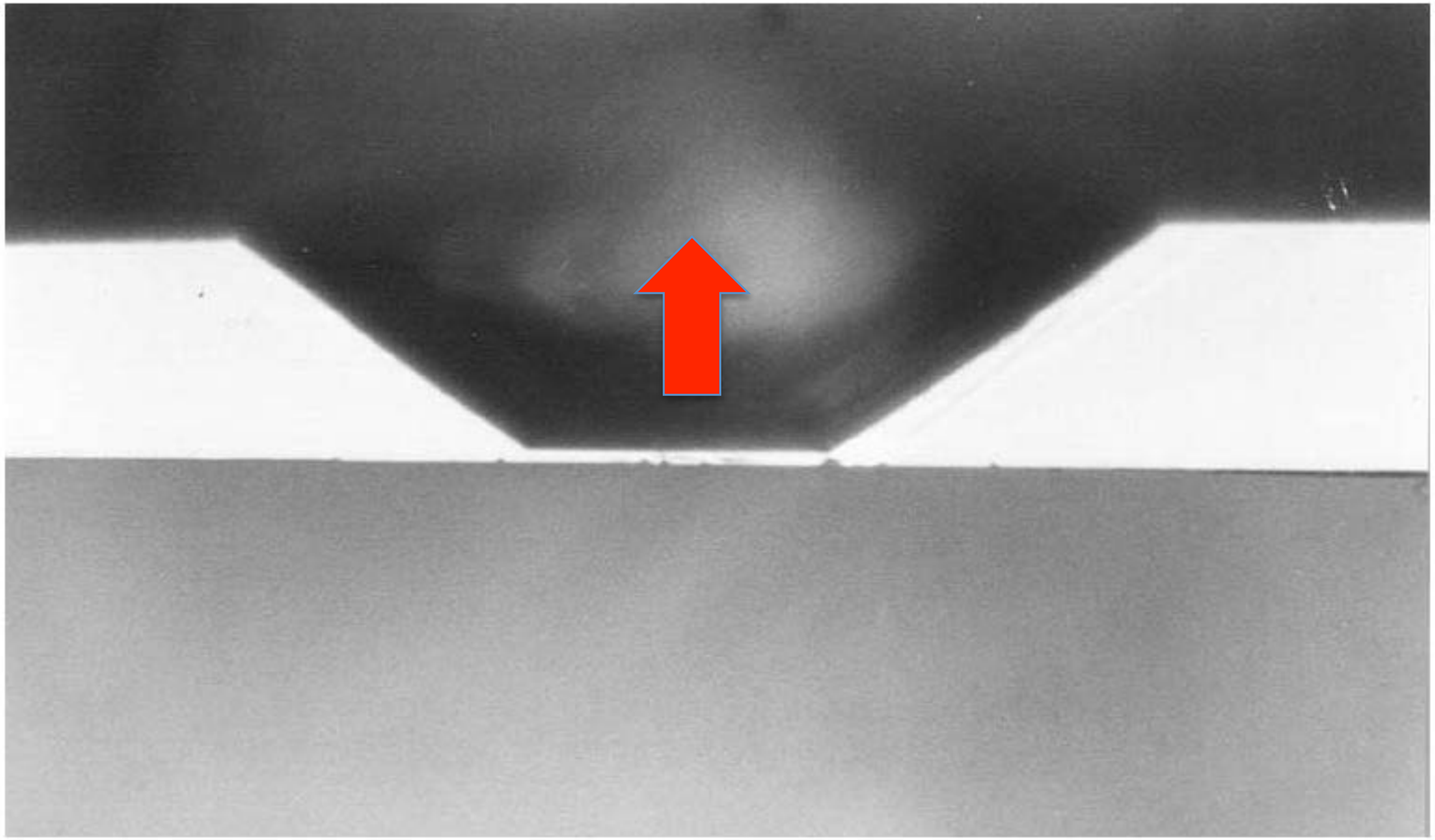
最初の発振: 1979



[1979IGA] H. Soda, K. Iga, C. Kitahara and Y. Suematsu, "GaInAsP/InP surface emitting injection lasers", Jpn. J. Appl. Phys., vol. 18, pp. 2329-2330 (1979)

6-micron cavity VCSEL 1982

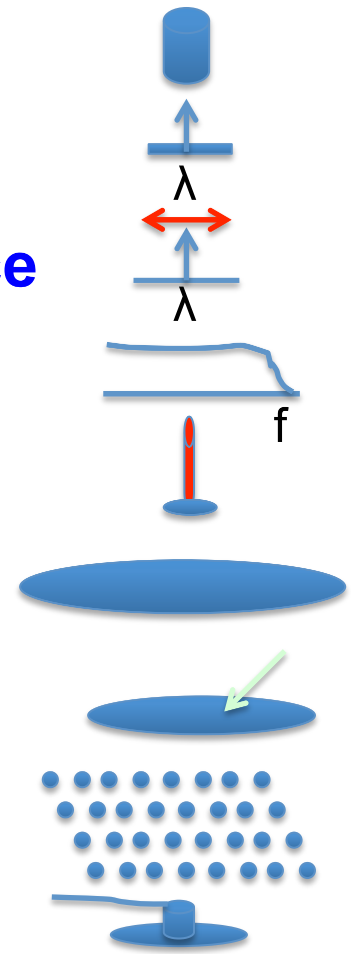
Very Thin Laser: A Big Breakthrough



6 μm

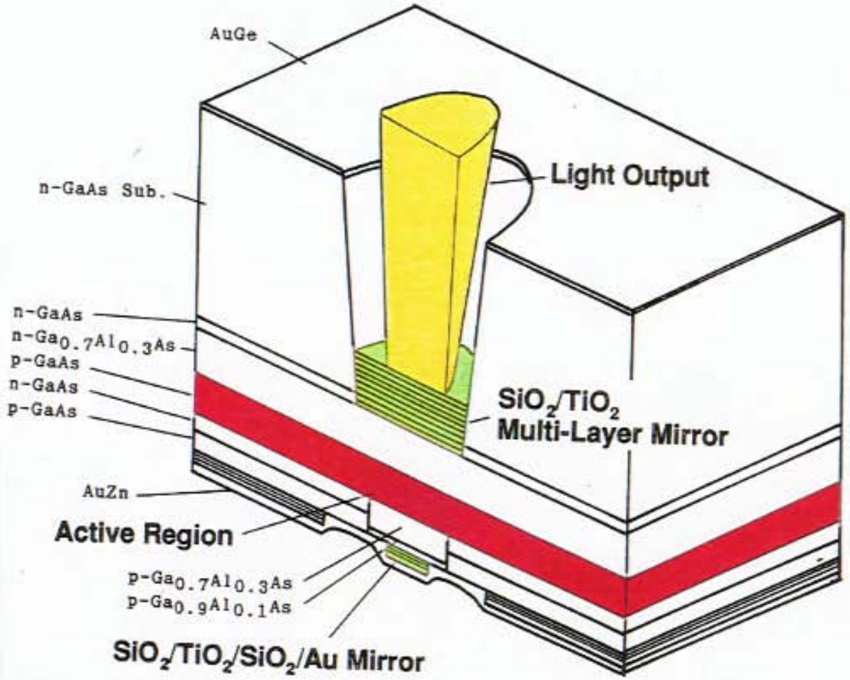
VCSEL Advantages

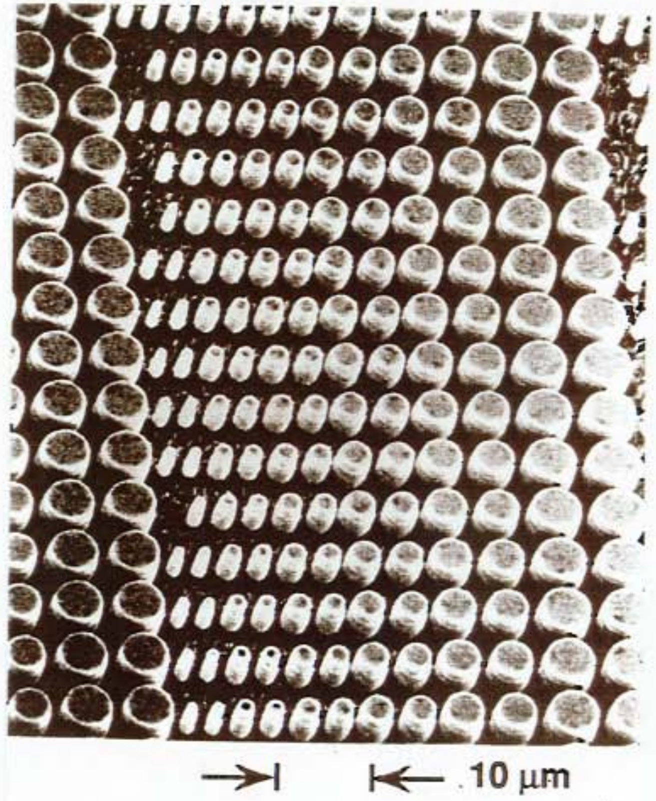
a) Ultra-low power consumption: Small volume
b) Pure spectrum operation: Short cavity
c) Continuous spectrum tuning: Single resonance
d) High speed modulation: Wide response range
e) Easy coupling to optical fibers: Circular mode
f) Monolithic fabrication like LSI
g) Wafer level probe testing
h) 2-Dimensional array   2D Scaling Law
i) Vertical stack integration with micro-machine



j) Physically small

Epoch Making VCSELs (2)





1988

K. Iga, F. Koyama, and S. Kinoshita, IEEE J. Quant. Electron. 24, 1845(1988).
F. Koyama, and S. Kinoshita, and K. Iga, Appl. Phys. Lett. 55, 221, (1989).

J. L. Jewell, A. Scherer, S. L. MacCall, Y. H. Lee, S. J. Walker, J. Harbison, and L. T. Florez, Electron. Lett. 25, 1123(1989).

After Room-Temperature CW

1989 Break

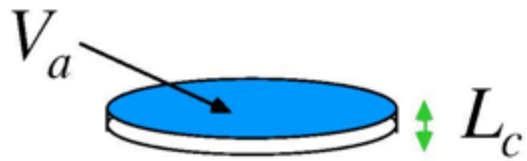

ZERTIFIKAT
über die Echtheit eines Bruchstückes der
Berliner Mauer
ZERTIFIKAT
Berliner Mauer 9. Nov. 89

2001 National Nanotechnology Initiative (NNI), USA

Vertical Cavity Surface Emitting Lasers are another device that relies on superlattices with nanometer thick films. VCSELs were first demonstrated in the 1970s by the Tokyo Institute of Technology (Japan) and became a commercial reality in the 1990s following innovations at ATT and DARPA funding.

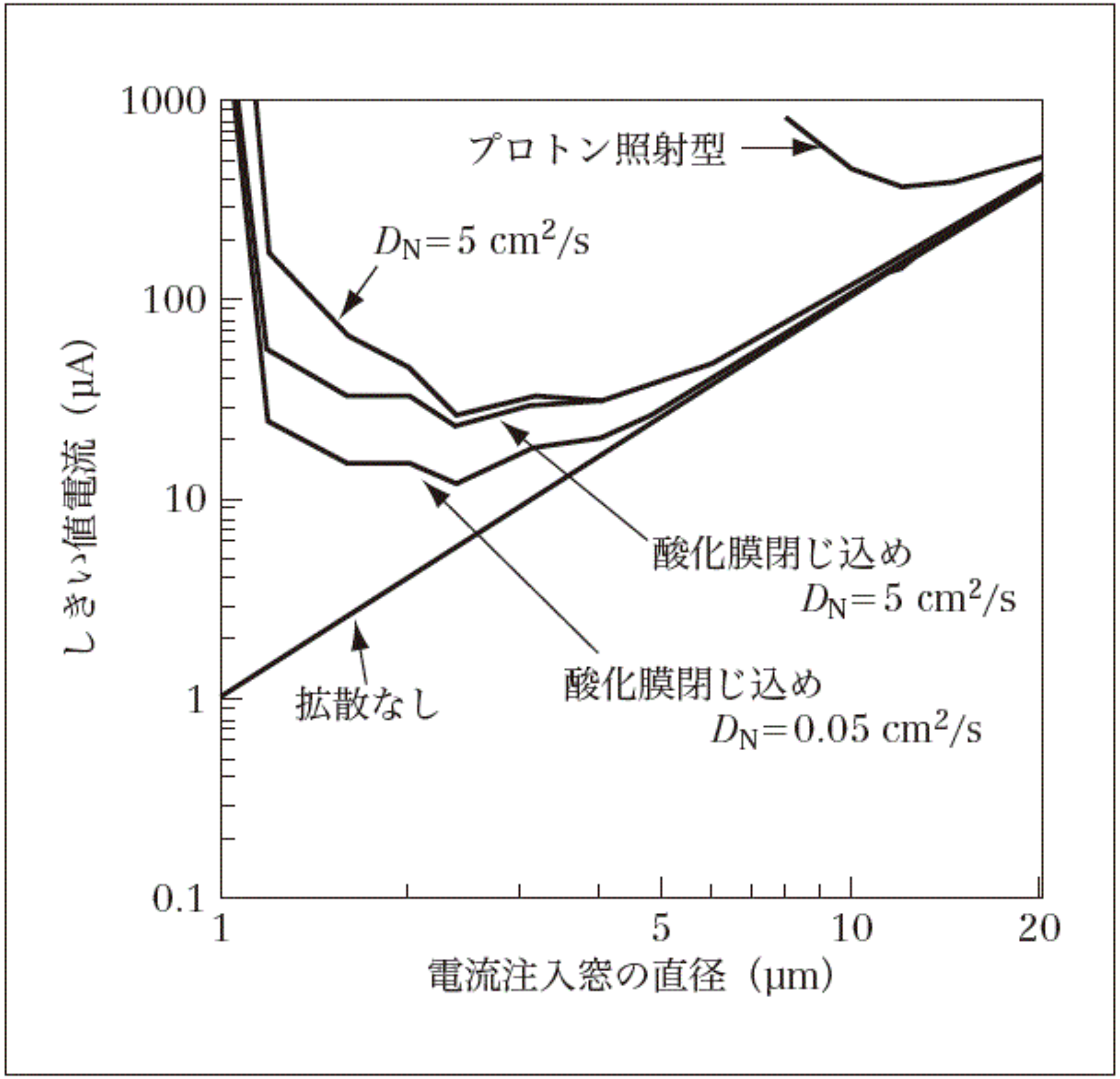
Scaling Law

Threshold	$I_{\text{th}} \propto V_a$
Relaxation Frequency	$f_r \propto \sqrt{1/V_a}$
Tuning Range (FSR)	$\Delta\lambda \propto 1/L_c$
Spontaneous Emission Factor	$C \propto \frac{1}{V_a}$

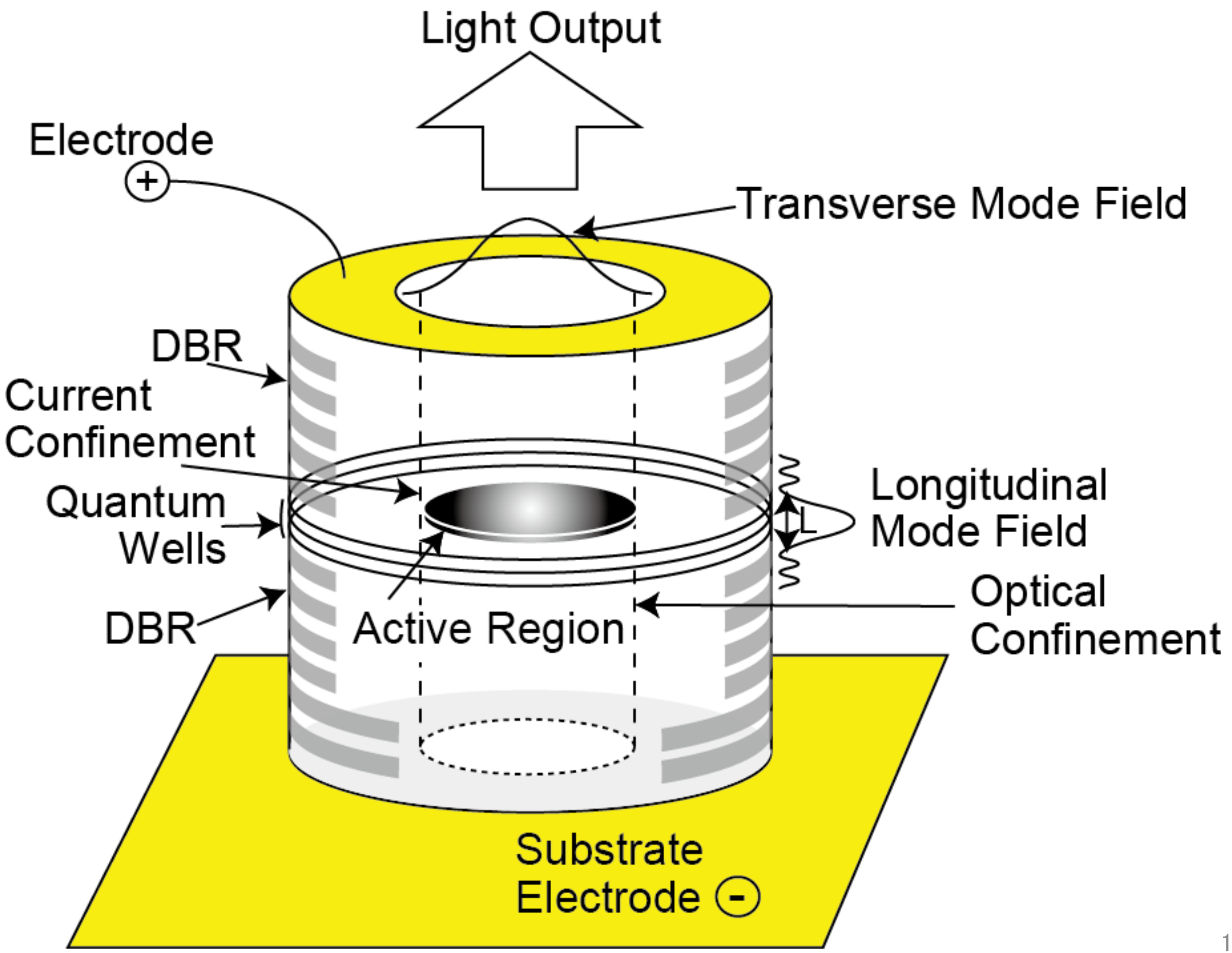


Small is Smart !

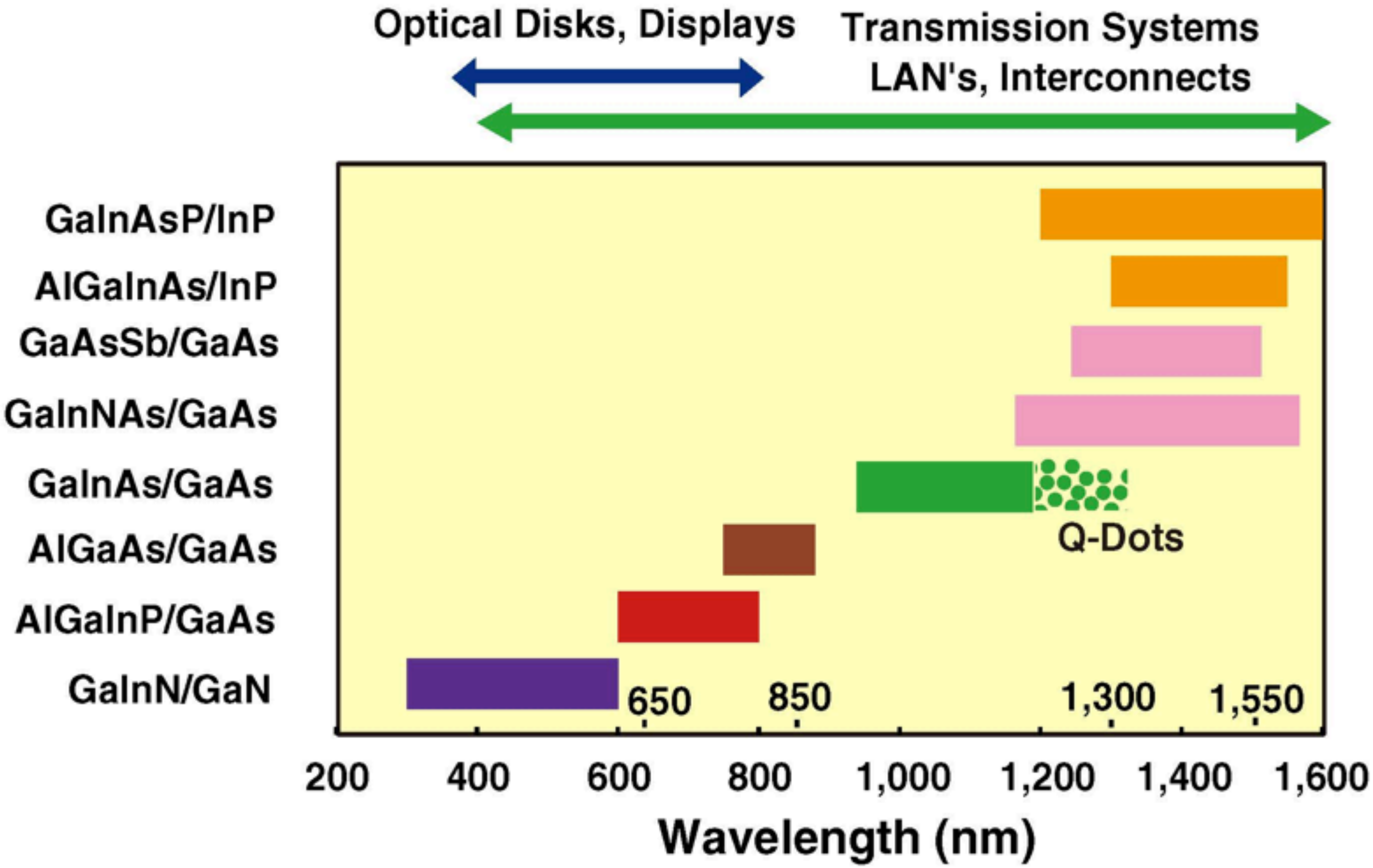
Threshold Current



Surface Emitting Laser : Its Model



Optical Spectrum and Materials



VCSEL Video Demo

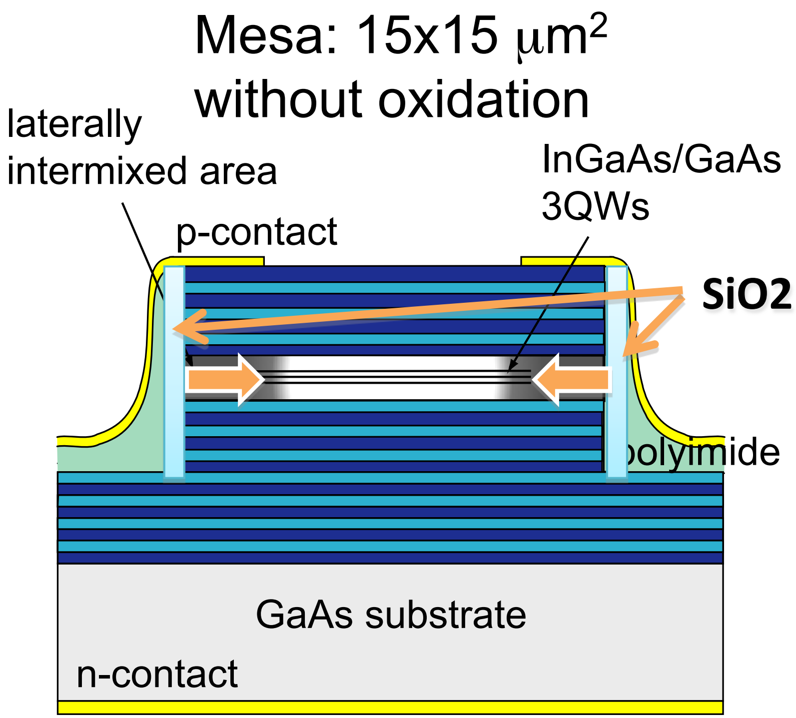
After Genichi Hatakoshi, Toshiba

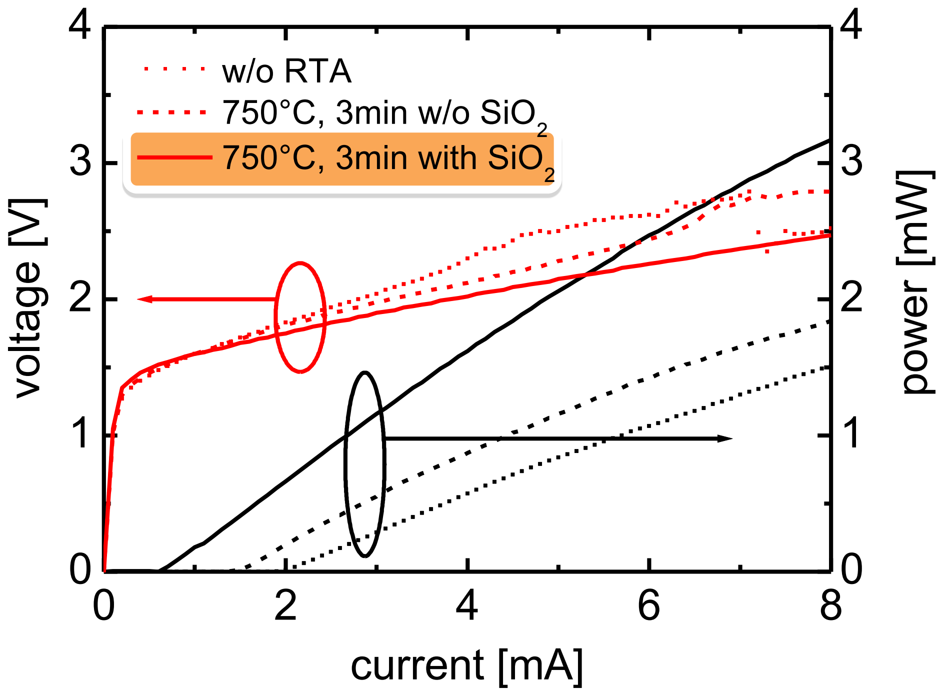
Competition of Threshold Reduction

1990-2000
Tokyo IT, Bell Labs, Bell Core, UCSB, USC, U.TX, U. Ill, UCB, TNM, U. Ulm, TU Berlin, TU Munchen, U. Wuertzburg, Industries,,,,,,

Quantum wells and dots, AlAs oxidation, High quality conductive mirrors, ,,,,

Laterally Intermixed QW VCSEL



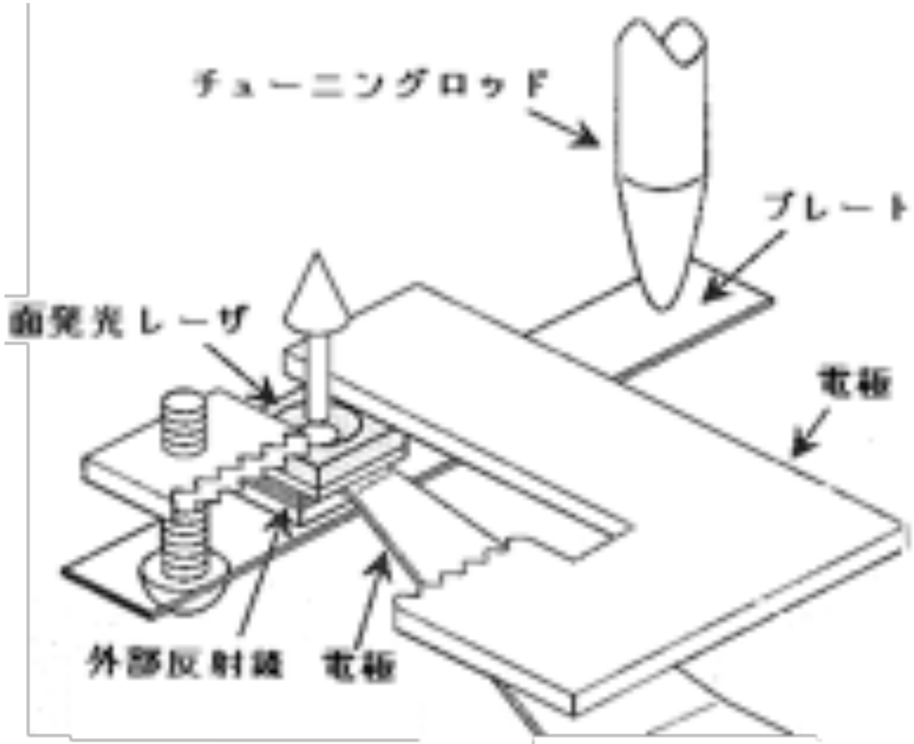


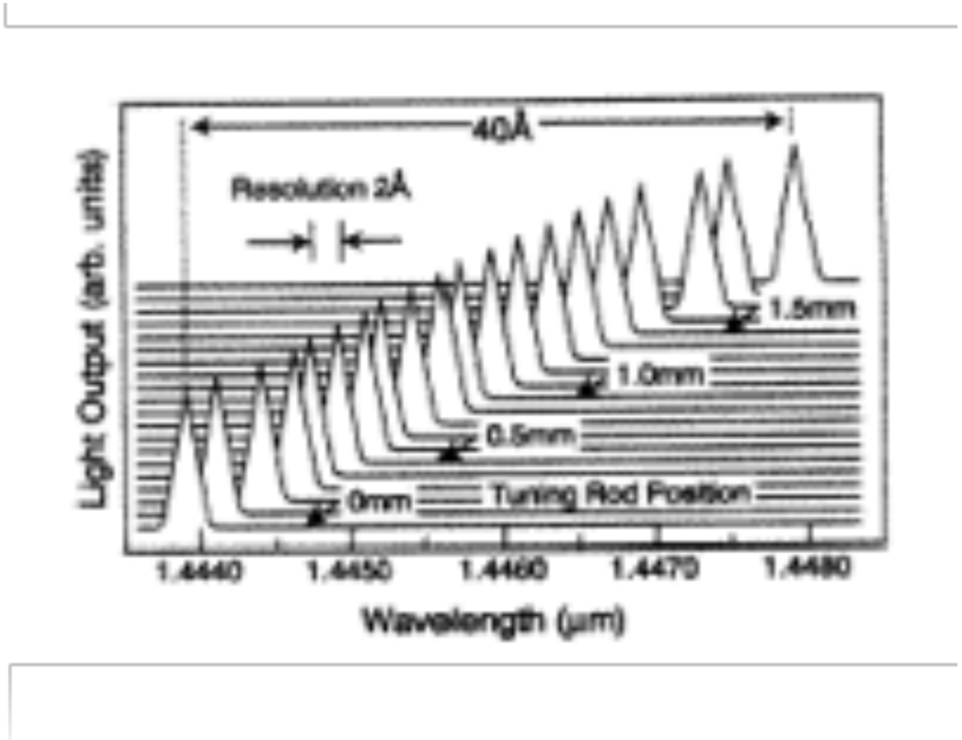
Quantum structure intermixing from mesa side-wall offers **carrier confinement for lower thresholds**

	I_{th}	η_d	$P(I$=8mA)
w/o RTA	2.0mA	0.20	1.5mW
intermixed	**0.6mA**	**0.35**	**3.2mW**

Sugawara and Miyamoto, Electron. Lett., 2009

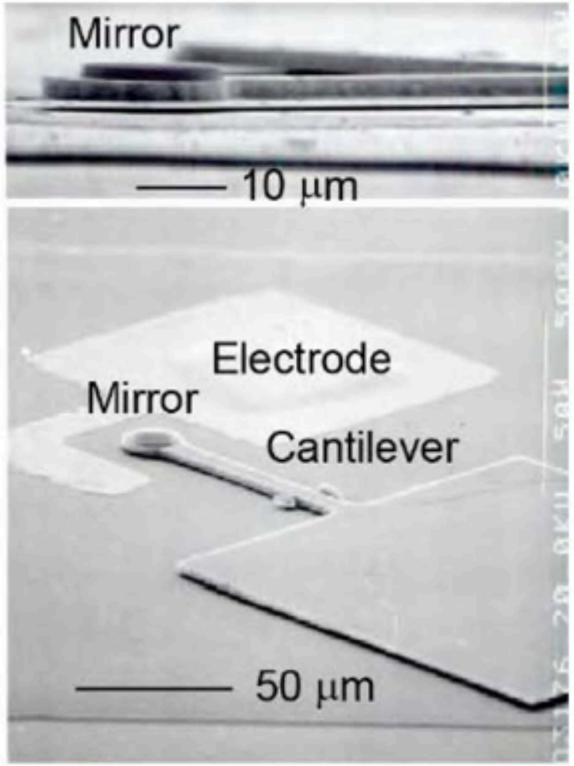
First Wavelength Tuning：1992



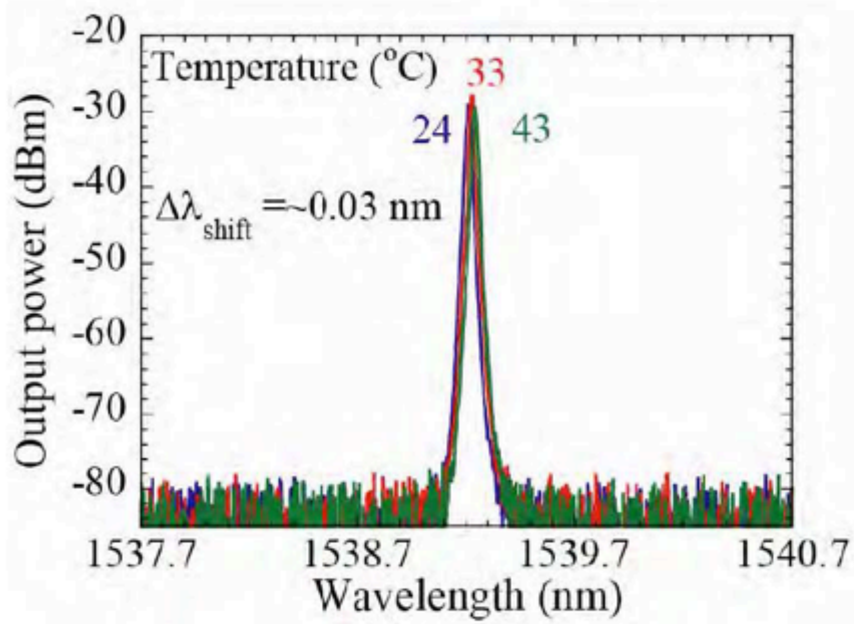


N. Yokouchi, T. Miyamoto, T. Uchida, Y. Inaba, F. Koyama, and K. Iga:
IEEE Photon. Technol. Lett., vol. 4, no. 7, pp. 701-703, Jul. 1992.

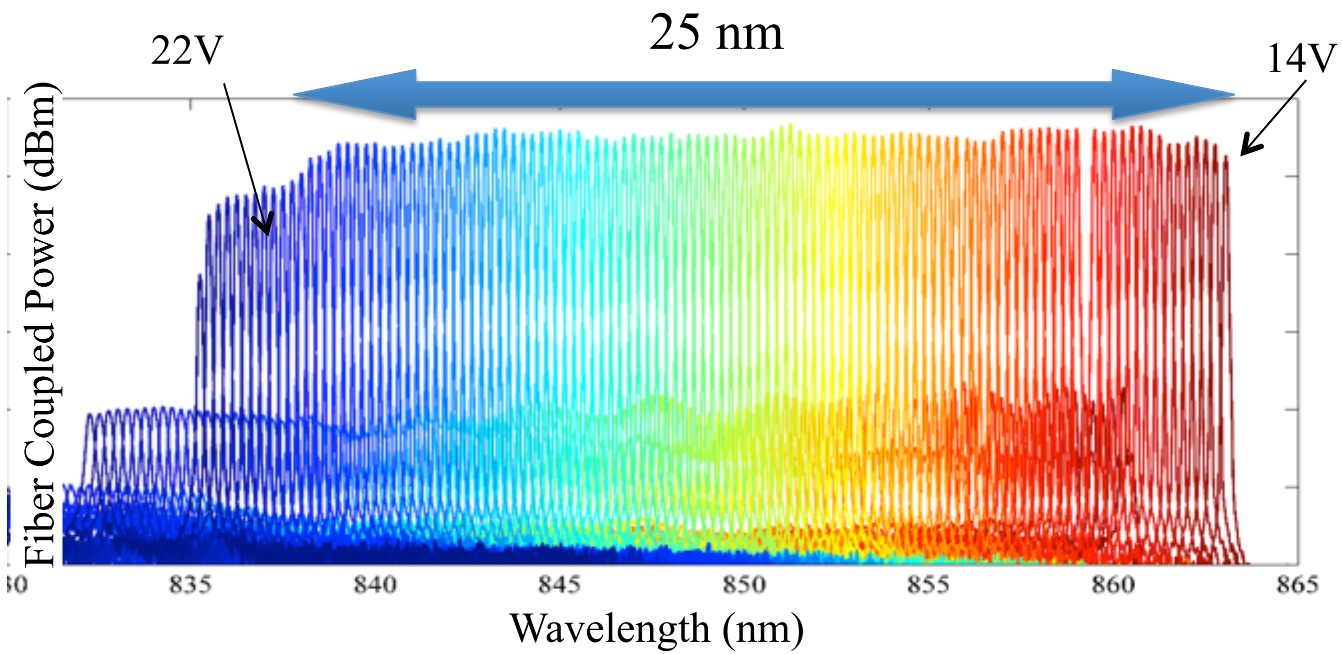
Athermal InP-based 1.55 μm VCSELs



$d\lambda/dT$=0.0016 nm/K
50 times smaller than DFB LD!



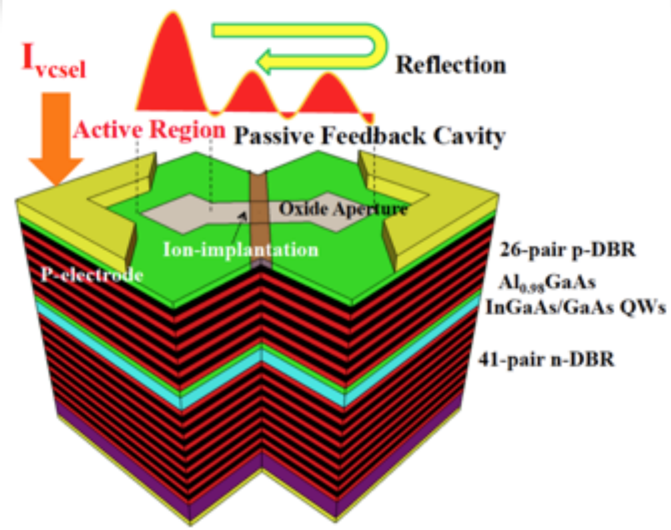
Janto, Hasebe, Nishiyama, Caneau, Sakaguchi, Matsutani, Koyama, and Zah
ISLC PD1.1, 2006

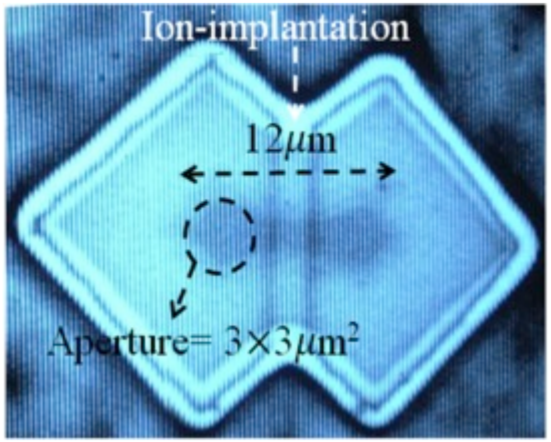


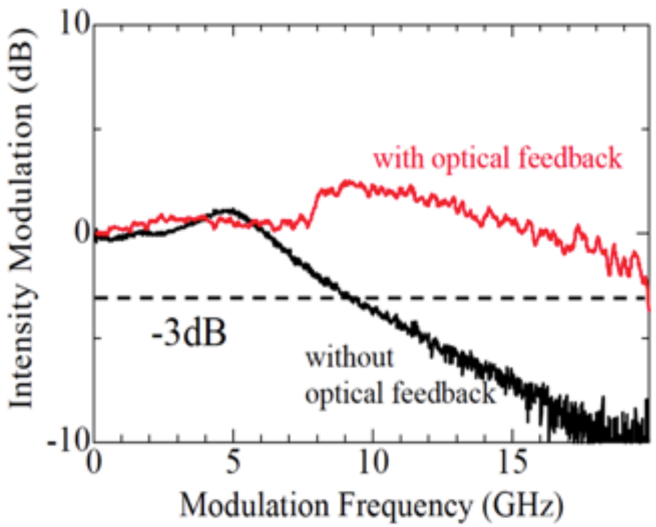
After Fumio Koyama, 2016

図9

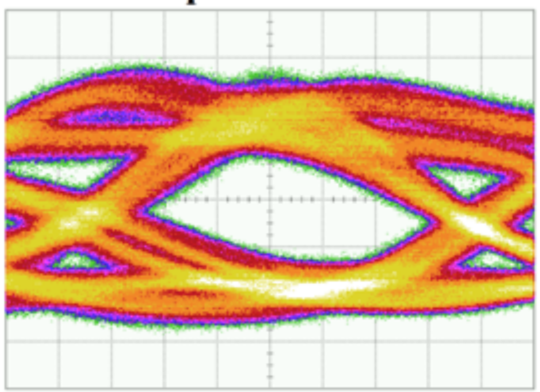
High-speed Transverse Coupled Cavity VCSEL







with optical feedback

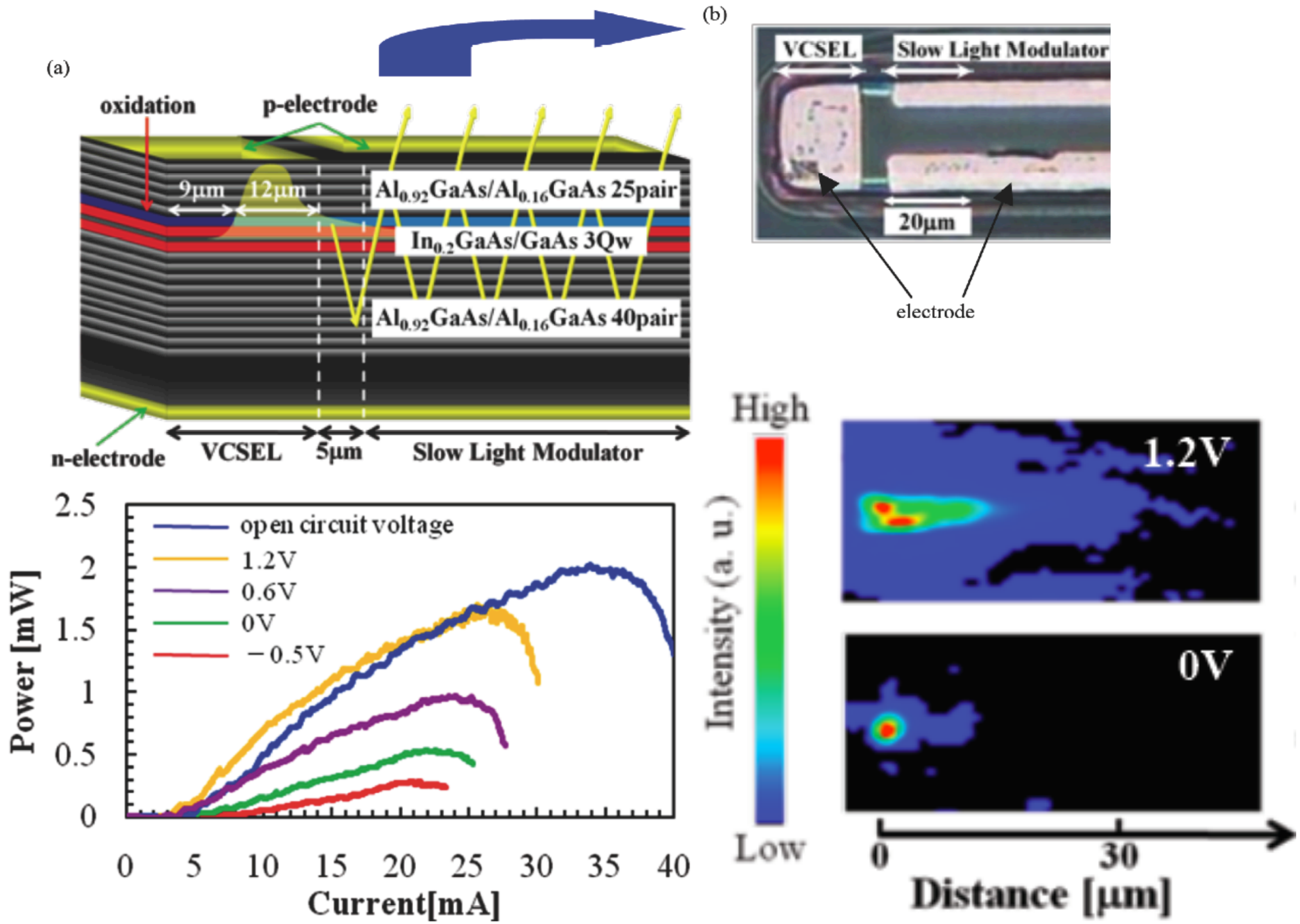


36Gbps PRBS, I_b=10mA
Extinction Ratio 4dB

Bandwidth Enhancement thanks to Photon-Photon Resonance
3dB Bandwidth > 20GHz (doubled)

Dalir and Koyama, IEEE Photonics Conference, PD 2013

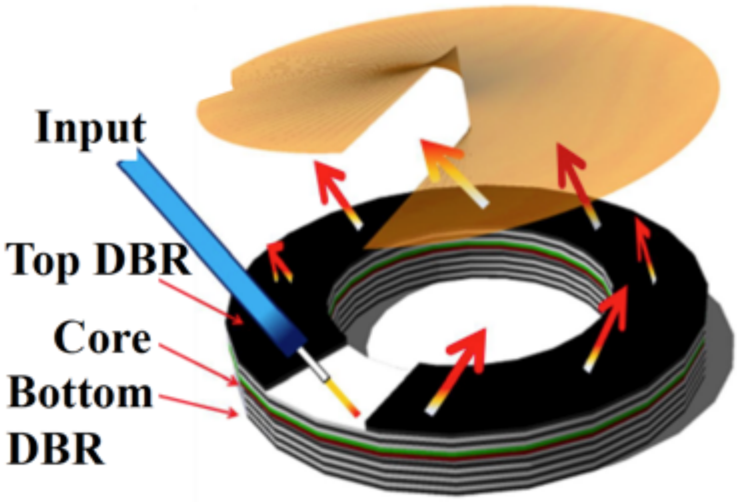
Lateral Integration of VCSEL and Slow Light Modulator



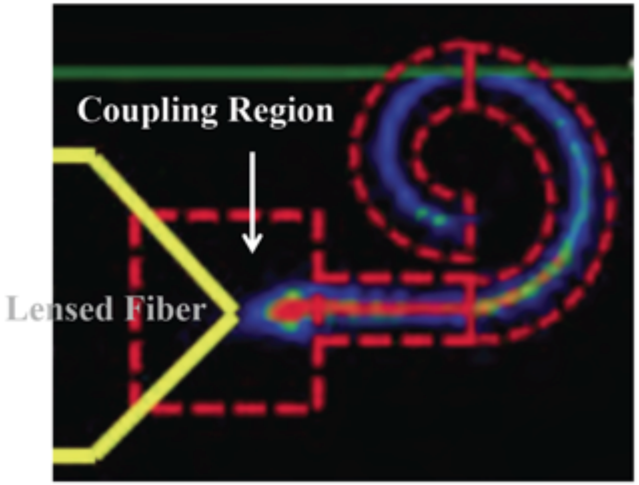
Extinction Ratio: 5dB@1.2V, Effective Length < 20μm

Shimada, Fuchida and Koyama, ECOC 2011

Creation of Vortex Beam based on VCSEL Photonics

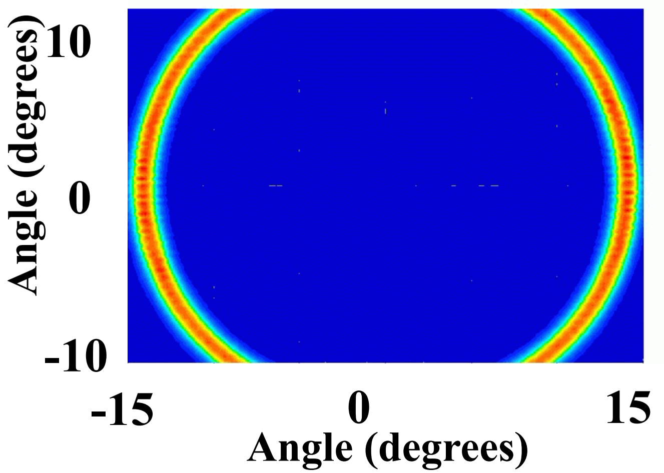


Near Field Pattern

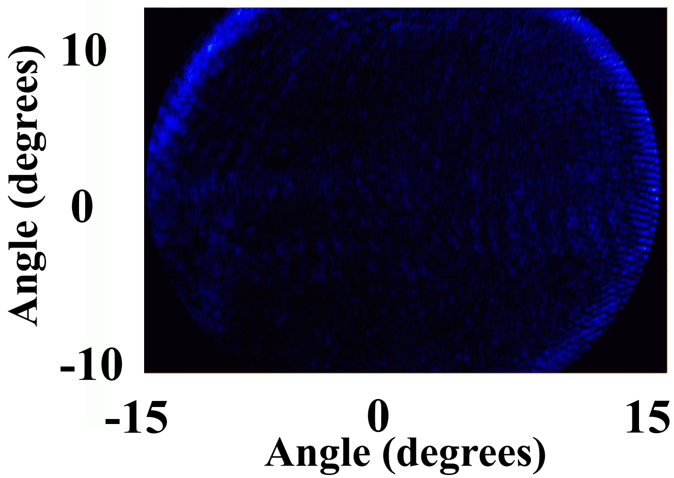


Far Field Pattern

Simulation



Experiment

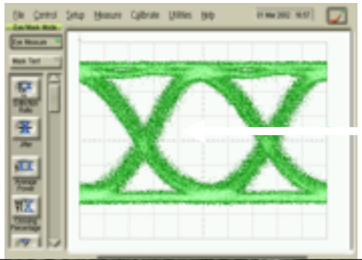


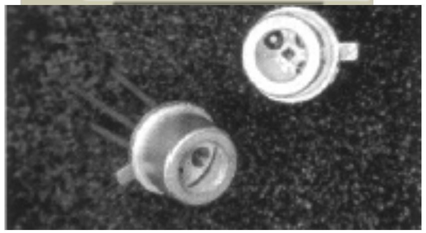
Mochizuki, Gu, Matsutani and Koyama, CLEO 2013

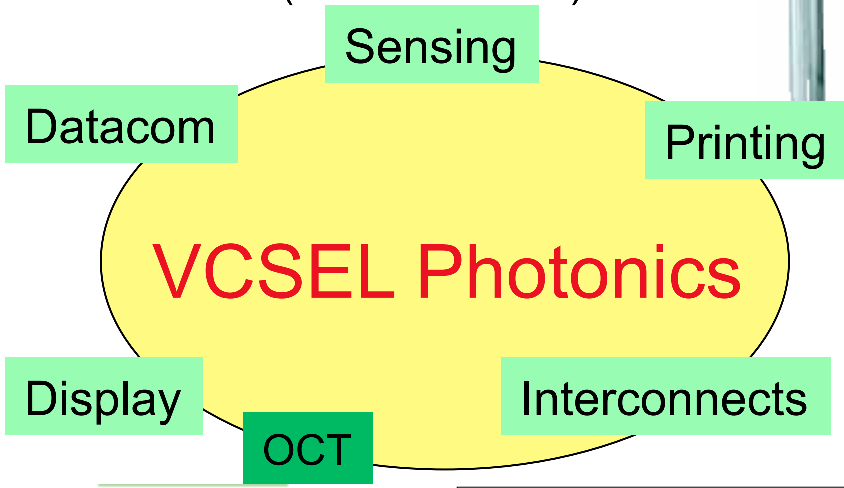
VCSEL Applications

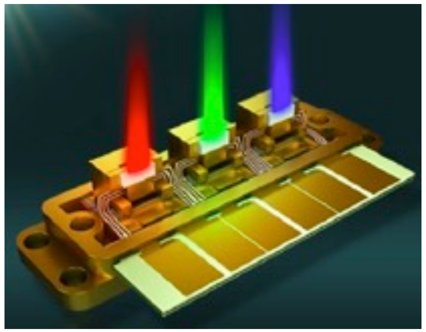
after Microsoft
(Ulm Photonics)

after FujiXerox

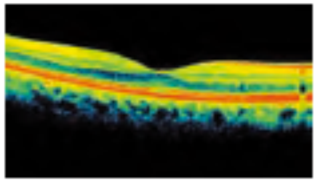




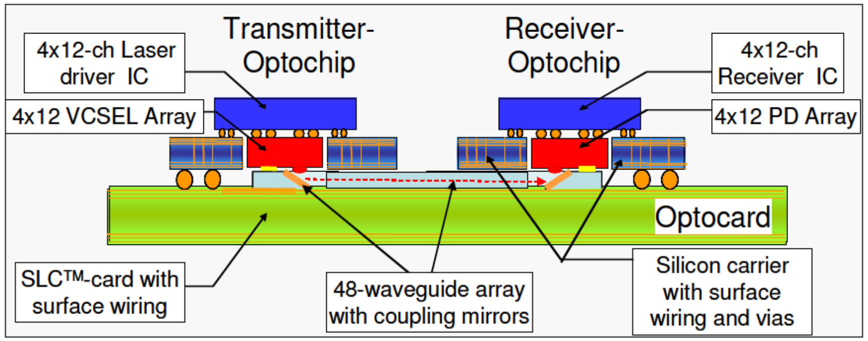




after Novalux



OCT (Image of Retina)
http://www.oct-optovue.com/



after IBM/Agilent

VCSEL Applications

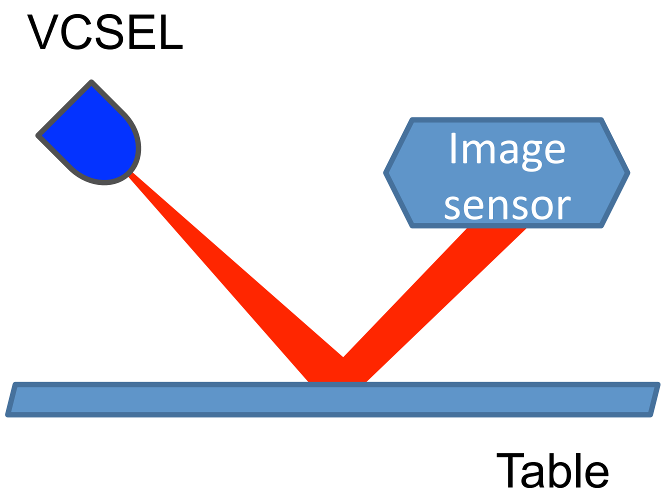
1. Optical Communications	LANs, Optical link, Mobile link, etc.
2. Interconnects	In Super–computer,
3. Data transfer	High speed/Parallel Links, etc
4. Optical Memory	Disk, Near field, Multi-beam, Initializer, etc.
5. OE Equipment	Printer, Laser pointer, Mobile tools, Home appliance, etc.
5. Information Processing	Parallel optical processing, etc.
7. Optical Sensing	Optical fiber sensing, Bar code reader, Laser mouse, Encoder, etc.
8. Displays	Array light source, High efficiency light-source, Projectors
9. Illumination	Multi-beam search-light, Micro-illuminator, Adjustable illumination
10. Power Optics	Engine igniter, Laser radar, Manufacturing
11. Quantum Optics	Atomic clock, Optical clock signal,

Laser Mouse

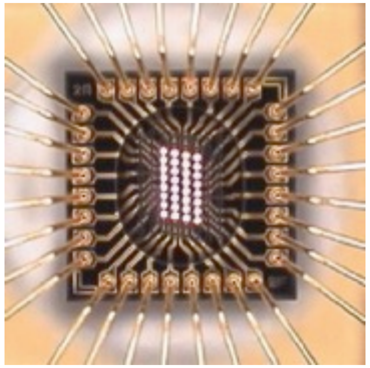
1B（1000,000,000) Pieces Shipped in the World.

After Microsoft;
VCSEL by Ulm Photonics

- High sensitivity
- Available on transparent or luster table
- High efficiency
- Low power consumption
- Long battery-operation
- ***VCSEL is the key light source for optical sensing systems.***



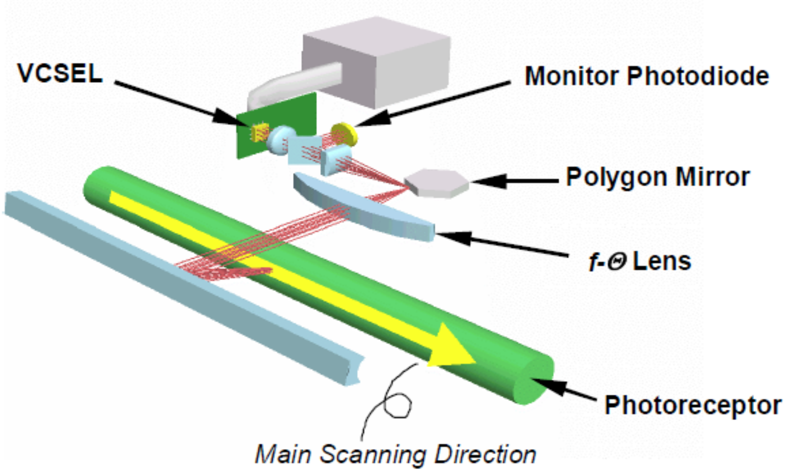
VCSEL Laser Printer



4x8 VCSEL array

- 2-Dimensional *VCSEL* Array.
- High speed and Ultra-fine Resolution.
  (14 pages/ min. 2400 dots/inch)

Light exposure system



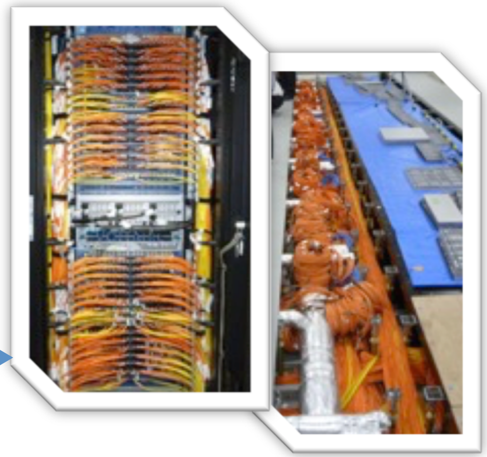
After Fuji Xerox: World First Demonstrator

Supercomputer : TSUBAME ~~2.0~~2.5

Nov. 2011 5th in Top500: , June 2-11 Greenest in Green500

Top500/Green500/Graph500: Top in the World, 2012

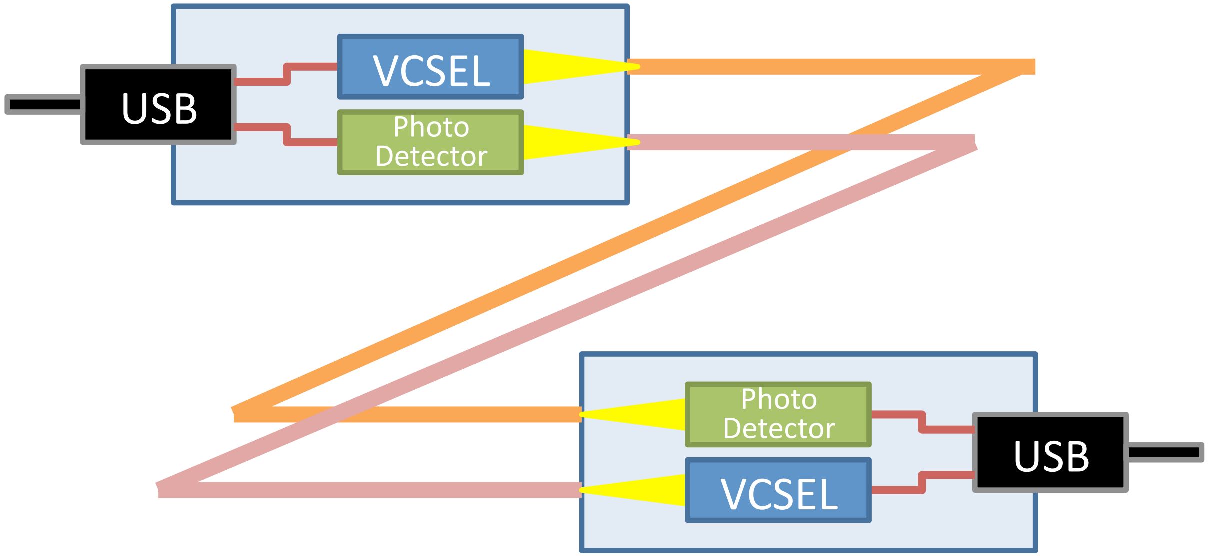
GSIC Prof. Satoshi Matsuoka
Cooperators
NEC（Total System Buolding）
HP
NVIDIA
Microsoft
Voltaire (Infiniband)
Other several



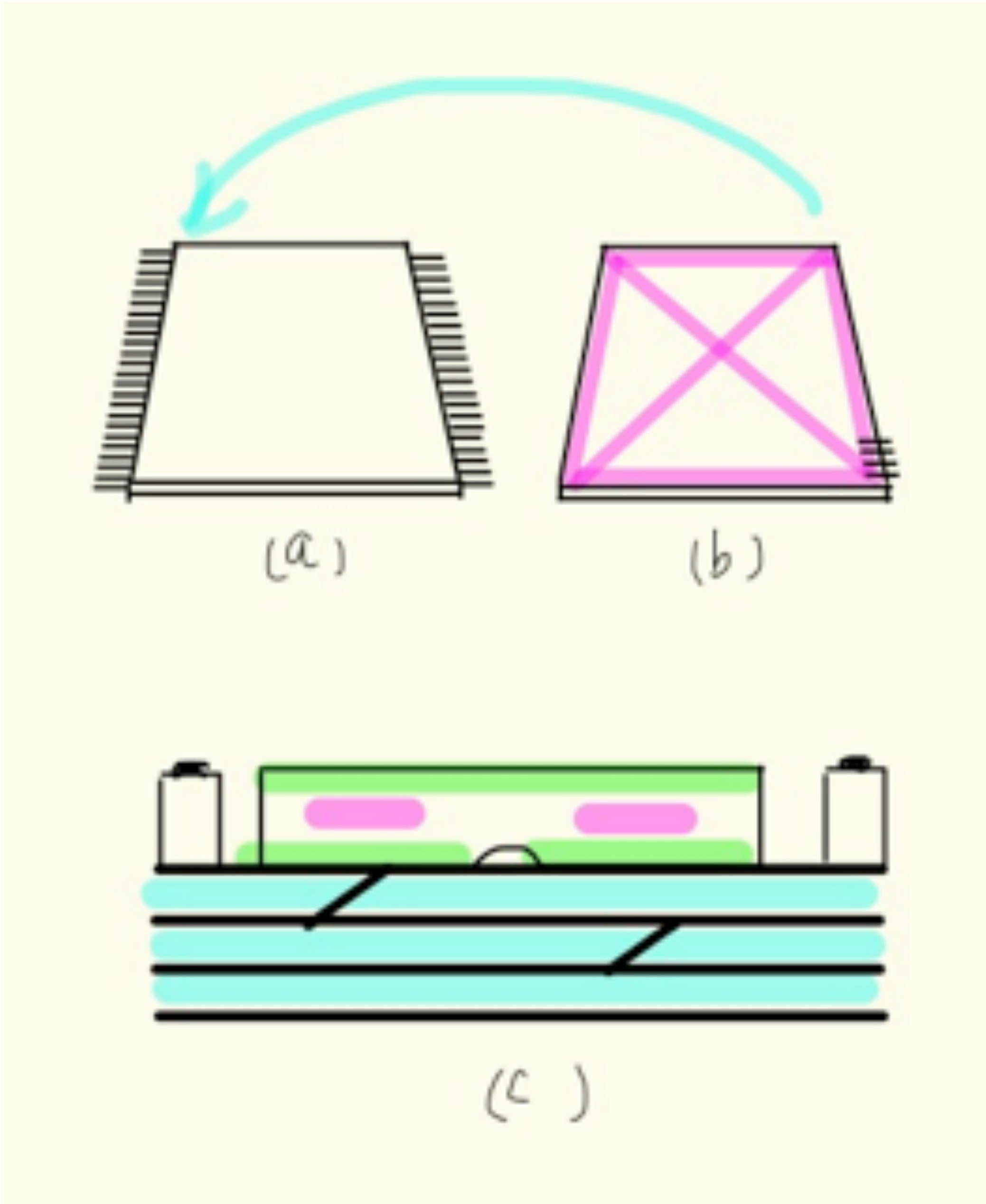
Peak：2.4 Peta Flops Leader of CPU+GPU
(From TSUBAME1.2)
Top500 ：1.19 Peta Flops
Storages：11 Peta Bites
(SSD:200Tera+ HDD:7.2 Peta +Tape:4 Peta)
Optical Interconnects：Fibers 3500, Length=100km
(cf. IBM Sequoia: 330,000 VCSEL)

Optical Active Cable

- Currently, USB, video-interface, and various data-cables are available as the **optical active cable**.



VCSEL Interconnects : Level 4 & 5

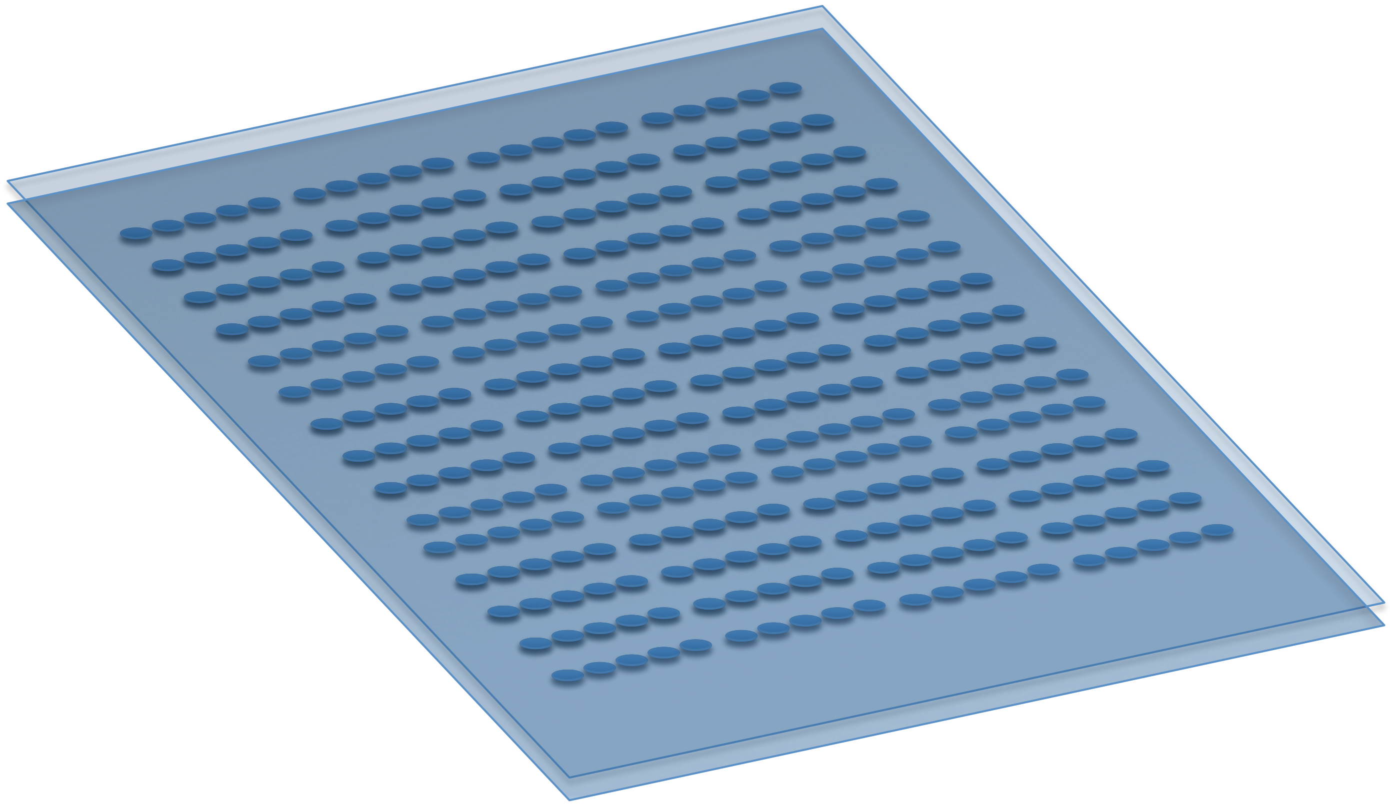


K. Iga, O plus E, Vol. 38, No. 1 p.32, 2016

A Large Scale Array

Talbot-Cavity-Coupled Coherent Array

1mW x 100 x 100 x 1000= 10kW



VCSEL Market

By 2020, >2500M$

Data Com
High Power
Sensors

Summary

VCSEL Technology;

Started from Minor Reputation.
Generating a Big Innovation.

Featuring;

a) Low Power Consumption, Good for Green ICE
b) High Speed Electronics and Photonics
c) 2-D or 3-D Configuration
d) Good for High Power Application
OK

Future;

Will Generate Smarter Ideas Never Thought.

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