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Forty years of vertical-cavity surface-emitting laser: Invention and innovation

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Forty years has passed since I conceived the idea of a vertical-cavity surface-emitting laser (VCSEL) in 1977. This review is focused on its research and development by featuring host technologies that contributed to the realization of usable devices. After numerous innovations, the VCSEL is now generating new applications such as high-speed local area networks, computer mice, parallel optical interconnects, laser printers, face recognition systems, and various optical sensors.

1. Introduction

I conceived of a surface-emitting laser on March 22, 1977.[1] My sketch of the idea is shown in Fig. 1. In contrast to the conventional Fabry–Perot edge-emitting semiconductor lasers, this invention consists of a laser cavity vertical to the wafer surface on which many layers are monolithically grown, including an active layer. Soon later, it began to be called the vertical-cavity surface-emitting laser (VCSEL).

I have written several reviews on VCSEL before,[2–5] but in this article, the VCSEL is described from some different aspects and with new information.

I presented an invited talk at MOC2017[6] and this paper is based on its digest. The newly added contents include the features of the VCSEL concept, the motivation behind the invention, a breakthrough for the realization, and several technologies that became essential for later devices such as quantum wells, semiconductor Bragg reflectors, and AlAs oxidation technique. I will describe the first successful continuous tuning of lasing wavelength by a mechanical method, which became the scheme of MEMS-tuned VCSEL in later years. As the benchmarks of development, early-stage patents and similar works are introduced. Finally, recent applications of VCSELs are reviewed. Single- and multi-transverse mode devices have shown their applicability in related optoelectronics systems. For better understanding, eight figures and two tables are added. The iThenticate similarity index is 16% against 48 registered papers.

First, let us look at the motivation of research based on the conception of VCSEL. Second, the mode behaviors and related applications, and lastly, the current progress of applications are discussed. After 40 years of research and development, a new optoelectronics field has been opened, which will be introduced later.

2. Motivation of invention

2.1 Conception

During the research on semiconductor lasers by our group starting in 1970 at Tokyo Institute of Technology, I was dissatisfied with the conventional semiconductor lasers from the viewpoint of their fabrication and device characterization. The cavity of the conventional semiconductor lasers was fabricated by cleaving wafers, i.e., by cutting an epitaxially grown wafer along a specific crystal plane (100) with the cavity length of approximately a few hundred micrometers. In the initial stage of production, the cleaving process was carried out using a kind of surgical knife. It was far from mass production, for example, on the order of 10^9 pieces. As another disadvantage originating from the edge-emitting laser structure, device characterization was possible only after the cleaving process was completed, which made device characterization difficult, including the initial quality test on a wafer scale. This feature had also led to the difficulty in realizing two-dimensional semiconductor laser arrays.

Fig. 1. A sketch of my VCSEL idea in 1977.[1]

Another consideration was how to realize a single-mode laser, that is, the lateral mode and longitudinal mode. Around 1976, we were interested in a short-cavity semiconductor laser and the possibility of maintaining in dynamic single-mode capability by making a short cavity to widen the free spectrum range (FSR). One of the conclusions made on the basis of computer simulation was that we must make the cavity length smaller than 50 μm. This result was presented in 1976 at the IEEE Semiconductor Laser Conference in Nemunosato, Mie Prefecture and reported in a paper.[7]

The third problem was how to control the lasing frequency, namely, how to guarantee the reproducibility of lasing frequency. It is almost impossible to precisely control the oscillation frequency of Fabry–Perot edge-emitting lasers lasing under the multimode condition. Also, the cutting position that determines the cavity length may have an error much larger than wavelength. Some grating filters are used to control oscillation frequency, as in distributed feedback (DFB) and distributed Bragg reflector (DBR) lasers. Since resonant frequency is determined by the grating period, the precise frequency should be dependent on waveguide structures that affect the equivalent index.

After critical consideration to solve the aforementioned issues associated with conventional edge-emitting lasers, I reached the conclusion that the laser cavity should be made vertical, not transverse to the semiconductor wafer surface. I thought that the cavity can be made of semiconductor layers and/or dielectric layers, which can be fabricated by semiconductor processes, not by manual cleaving processes.

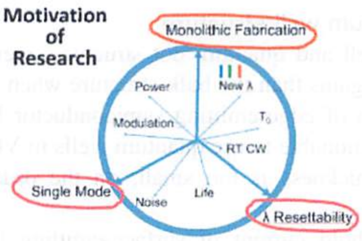


Fig. 2. (Color online) The motivation of research leading to VCSEL invention.

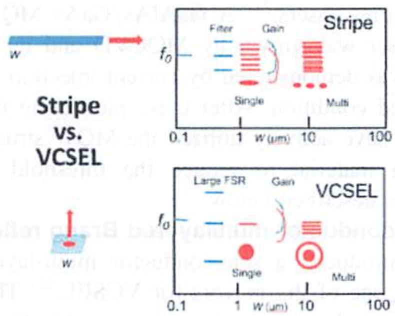


Fig. 3. (Color online) The difference between edge-emitting stripe laser and VCSEL.

2.2 Motivation

The motivations of its invention were to realize a laser
(i) manufacturable by a monolithic process,
(ii) with single-mode operation, and
(iii) with wavelength reproducibility.

The motivations are illustrated in Fig. 2. The items inside the circle are those that were achieved in industries in the 1970s. We took a different way of fulfilling the aforementioned three conditions.

2.3 What is the difference?

The difference between stripe lasers and VCSEL for obtaining single-mode operation is shown in Fig. 3.

The upper figure shows the behavior of edge-emitting stripe lasers. The horizontal axis is the stripe width and the vertical one shows the resonant frequency. Here, f_0 means the central nominal frequency. Even in the case of a small stripe width on the order of microns, the lateral mode can be single as indicated in the figure by an ellipse. On the other hand, resonance occurs at multiple frequencies. To realize single-frequency operation, some filtering structure is required, such as distributed Bragg reflectors.

On the other hand, we consider the case of VCSEL shown in the lower figure. For small-diameter VCSELs, the lateral mode is single and the longitudinal mode can also be single, since the free spectral range (FSR) is large owing to small cavity length.

3. Early stage of research

3.1 Initial device

On the basis of the initial idea of the surface-emitting semiconductor laser, we pursued analytical and experimental research on this new structure. The concept and the first experimental results on spontaneous vertical light emission from a GaInAsP/InP device were presented at the 25th Spring Meeting of the Japan Society of Applied Physics and Related Societies in March 1978.[8] The second report was presented at the 26th Autumn Meeting of the Japan Society of Applied Physics and Related Societies in November 1978. The paper consisted of results from the analysis of mirror reflectivity for vertical cavity laser and experiments on vertical cavity formation with a convex mirror surface.[9]

In 1979, we demonstrated the lasing operation of a GaInAsP/InP VCSEL under the pulsed injection current condition at 77 K.[10] This is the first demonstration of current injected VCSEL lasing oscillation and showed the possibility of VCSEL as a practical-semiconductor laser.

Subsequently, I and my group have been continuously conducting elaborate research and development of VCSELs and have achieved many basic results. Many papers that have contributed to the growth of VCSEL devices and related applications have been published.

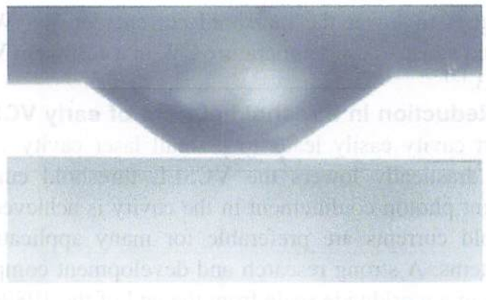


Fig. 4. Cross section of a 6 μm cavity.[11]

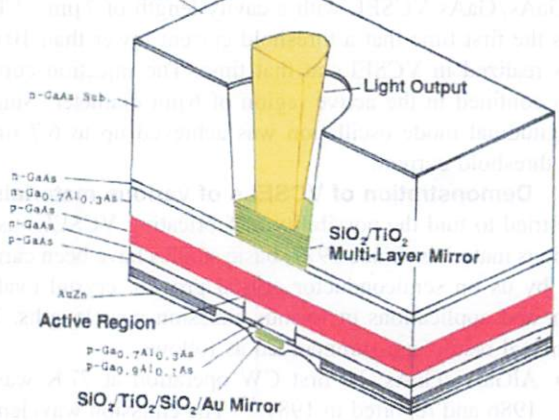


Fig. 5. (Color online) VCSEL that achieved the first room-temperature CW operation.[12,13]

3.2 Achievement for device realization

The primary breakthrough was the fabrication of a 6 μm cavity VCSEL that demonstrated a clear VCSEL mode even at 77 K, in 1982; i.e., single-mode, circular beam, and linear polarization.[11] In Fig. 4, we show an image of a cleaved cross section. The central portion corresponds to a laser cavity as narrow as 6 μm.

A pulsed threshold current as small as 6 mA was reported at room-temperature in a AlGaAs/GaAs VCSEL with a cavity length of 7 μm.[12] The first room-temperature continuous wave (CW) operation was achieved in 1988 by Koyama, Kinoshita, and I using a GaAs system as shown in Fig. 5.[13,14] This experiment demonstrated the possibility of VCSEL as an engineered semiconductor laser. We employed MOCVD crystal growth and multilayer mirror formation techniques to lower the threshold current density. We also achieved a near-room-temperature CW in a 1,300 nm VCSEL in 1993.[15]

3.3 Reduction in threshold current of early VCSELs

A short cavity easily leads to a small laser cavity volume, which drastically lowers the VCSEL threshold current if sufficient photon confinement in the cavity is achieved. Low threshold currents are preferable for many applications in ecosystems. A strong research and development competition ensued in a worldwide scale from the end of the 1980s to the 1990s, where I and my group were almost always of the forefront. As mentioned before, a pulsed threshold current as small as 6 mA was reported at room-temperature in a AlGaAs/GaAs VCSEL with a cavity length of 7 µm.[12] This was the first time that a threshold current lower than 10 mA was realized in VCSELs at that time. The injection current was confined in the active region of 6 µm diameter. Single-longitudinal mode oscillation was achieved up to 6.7 times the threshold current.

3.4 Demonstration of VCSELs of various materials

We tried to find the possibility of fabricating VCSELs using various materials. Since 1977, basic studies have been carried out by us on semiconductor crystal growth, crystal evaluation, and applications in various emission wavelengths. The principal results are summarized as follows.

- AlGaAs/GaAs: Its first CW operation at 77 K was in 1986 and reported in 1987.[15] The emission wavelength was 884 nm. The first CW operation at room-temperature was in 1988[12,13] as already introduced. Its emission wavelength was 894 nm.
- GaInAsP/InP: We successfully demonstrated the first lasing operation of VCSELs using GaInAsP/InP material systems by Soda et al. in 1979.[10] The emission wavelength was 1,180 nm at 77 K under pulsed current injection. The first CW operation at room-temperature in 1993[14] by Baba et al. and the emission wavelength was 1,374 nm.
- GaInAsN/GaAs: Long-wavelength lasers were realized on the GaAs substrates using the GaInAsN system lattice-matched to GaAs by Miyamoto et al.[16,17]
- InGaAs/AlGaAs: The record low CW threshold current of 70 µA at room-temperature was realized in 1995. The emission wavelength was 989 nm.[18]
- GaInN/GaN: A design was considered for blue-emitting VCSELs by Honda et al. and crystal growth by MOCVD was performed.[19]

As described in the list above, we have been contributing to the expansion of the emission wavelength region of VCSELs from long to near-infrared wavelengths, which has been effective for finding new VCSEL applications. Later on, red-emitting[20,21] and blue-emitting[22,23] VCSELs were investigated by many organizations to develop applications in visible regions.

4. Technologies introduced into VCSELs

As a forerunner of VCSEL research and development, we introduced new technologies into VCSELs for the first time in the world. Those included quantum well structures as the active region and semiconductor multilayered distributed Bragg reflectors as laser cavity mirrors. An external movable mirror was introduced for wavelength tuning.

4.1 Quantum well structure

Quantum well and quantum dot structures were verified to have higher gains than the bulk structure when applied to an active region of edge-emitting semiconductor lasers. It was thought questionable to use quantum wells in VCSELs, since the active thickness is too small, on the order of several nanometers.

The threshold current of surface-emitting lasers with a multi-quantum well (MQW) active region was theoretically estimated by Uenohara et al.[24] On the basis of the results, we introduced the MQW structure into the active region of surface-emitting lasers.[23] A GaAlAs/GaAs MQW surface-emitting laser was grown by MOCVD and its first lasing operation was demonstrated by current injection at 77 K the under pulsed condition. After these pioneering trials, many researchers have actively utilized the MQW structure as the active gain material to reduce the threshold current of VCSELs, as described below.

4.2 Semiconductor multilayered Bragg reflector

We first introduced a semiconductor multi-layered Bragg reflector as one of the mirrors for VCSEL.[25] This VCSEL cavity consisted of a pair of on n-$Al_{0.1}Ga_{0.9}As$/AlAs multilayer Bragg reflector and a Au/SiO_2 mirror. With this structure, besides the satisfactory high reflectivity achieved, manual processes are not necessary for fabricating a laser cavity. Soon after this achievement, a VCSEL was realized, whose principal components fully consisted of semiconductors. Both upper and lower mirrors of the VCSEL were formed with semiconductor multilayered Bragg reflectors. A drastic improvement in VCSEL fabrication productivity was accomplished. The semiconductor DBR is one important feature that I wanted to improve by eliminating the cleaving process in the formation of the cavity in conventional edge-emitting lasers. The semiconductor multilayered distributed Bragg reflector is utilized in almost all VCSELs today.

4.3 Movable mirror for frequency tuning

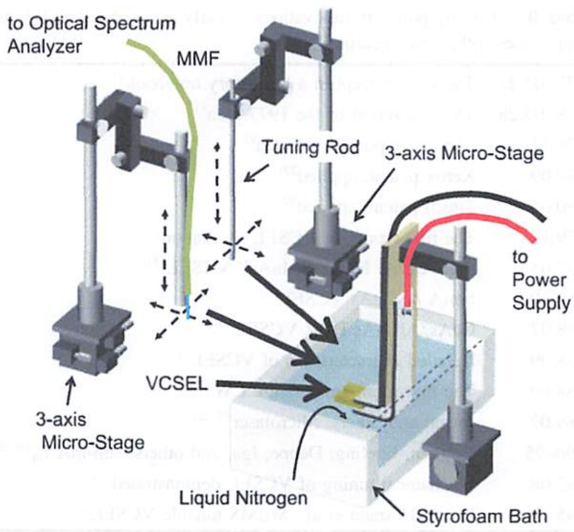
The reproducibility of laser frequency is one of the issues that I considered at the time of starting the semiconductor laser research. It is necessary to have some tunability to match the frequency to the system employed.

The VCSEL can emit light with pure single wavelength characteristics owing to its short cavity length. Since the exact emission wavelength is defined by the effective cavity length, continuous wavelength tuning is possible by changing the cavity length.

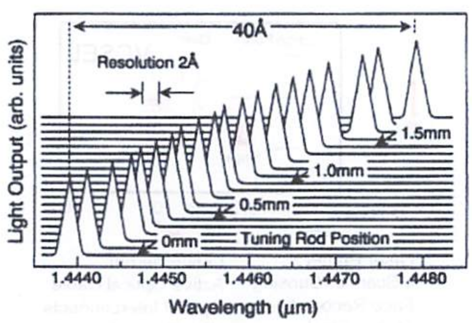
Continuous wavelength tuning of 18 Å was demonstrated by Chang-Hasnain et al.[26] Ebeling et al. reported tuning of 22 Å.[34] The principle concept was current injection through a newly added electrode into the n-DBR mirror to heat up.

To achieve a wide range of tunability, a mechanical tuning method was experimentally demonstrated by us with an InGaAsP/InP VCSEL.[27] One of the mirrors was replaced with a movable external mirror. It was driven mechanically by pushing a tuning rod, as shown in Fig. 6. The wavelength was changed continuously over 40–86 Å at 77 K without any mode hopping. This indicated clearly the possibility of continuous wavelength tuning in VCSELs, which later attracted interest for various applications.

A monolithic version of the external mirror VCSEL was realized by Chang-Hasnain et al. and showed a record high wavelength tuning range of 15 nm.[28] Frequency tunable



(a)



(b)

Fig. 6. (Color online) External-mirror-driven frequency tuning of VCSEL. (a) Experimental setup (drawn by N. Yokouchi). (b) Result of tuning.[27]

VCSELs are now becoming important light sources for spectroscopic sensing and Datacom with wavelength division multiplexing. Very recently, tunable VCSELs have been used for a ranging sensor in combination with a light beam deflector where the emitting beam angle depends on the wavelength. The wavelength-tunable VCSEL will open an extensive variety of applications.

5. Benchmarks of early stage of research

5.1 Patent by Tokyo Institute of Technology and Xerox

In the initial stage of VCSEL development, two patents for inventions were submitted. One was for the invention by Kenichi Iga, Yasuharu Sematsu, Katsumi Kishino, and Haruhisa Soda, all from Tokyo Institute of Technology, Japan that was applied on January 9, 1980 and was named "Surface-Emitting Laser". Hereafter, this is called the Titech Patent in this article.[29] Independently of the Titech Patent, R. D. Burnham, D. R. Scifres, and W. Streifer, all from Xerox Corporation, U.S.A. applied for a patent on September 13, 1979. Hereafter, this is called the Xerox Patent in this article. The patent was named "Transverse Light-Emitting Electroluminescent Devices".[30]

The Titech Patent and Xerox Patent were granted as independent inventions. Thus, two parties were considered as having independent patents.

Table I. Possible application areas of VCSELs.

Technical fields	Applications and systems
1. Optical communications	LANs (Ethernet), active optical cable, optical tranceivers, etc.
2. Computer/data-com	Optical interconnects, high-speed/ parallel data transfer, etc.
3. Optical memory	Near field, multibeam, etc.
4. Optoelectronic equipment	Laser printer, mobile tools, atomic clocks, etc.
5. Information processing	Optical processors, parallel processing, etc.
6. Optical sensing	VCSEL mouse, ranging and face recognition for smartphones, bar code readers, etc.
7. Displays	SHG green lasers, HMD, digital data transfer for 4K/8K TV, etc.
8. Illuminations	IR illuminations, autofocusing in cameras, etc.
9. Automotive electronics	Engine ignition, lidar, sensors, LANs, etc.
10. Power laser and machining	Manufacturing, soldering, cutting, etc.

However, the Xerox patent had not been recognized by us or the academic community regarding VCSELs until I received the 2002 Rank Prize together with Burnham and Scifres as co-recipients. I had received the Streifer Award in 1992 as the VCSEL initiator. This award was established by Xerox in memory of the late William Streifer who was one of the inventors named in the Xerox Patent. Aside from the patent, no notable research and development related to VCSELs has been seen from the Xerox group to the best of our knowledge, even though they performed outstanding work on high-power edge-emitting semiconductor lasers.

5.2 Jewell's microlaser

Many microlasers with the cavities of various sizes (3–100 μm) were manufactured on a GaAs substrate by Jewell et al. of AT&T Bell Laboratories.[31] The active region was a GaInAs single-quantum well of 100 Å thickness. The micro-cavity was formed by a pair of semiconductor DBR mirrors consisting of AlAs/GaAs multilayers. Later, the threshold currents of 1.5 and 1.1 mA under CW and pulsed conditions, respectively, were reported for a 5 μm square microlaser.[32] They possibly intended to study the micropillar lasers as the component of optical computers, which was the mission of the department at Bell Labs at that time. The micropillar structure was not applied in practical systems, since it is incompatible with full planar processes.

5.3 Threshold current reduction as a measure of single-mode devices

With promising results on VCSEL realized in our initial feasibility study, many organizations worldwide became interested in VCSELs and started their own research in the 1990s. To show the progress of VCSELs, we tracked the threshold current reduction achieved by our group at Tokyo Institute of Technology and by other organizations. The major players and their threshold current results are listed in Table I.

From the first half of the 1990s, the threshold current of VCSELs was further reduced from about 10 mA to 50 μA. Jewell et al. of AT&T Bell Laboratories achieved a threshold current of 1.3 mA (pulsed) with three GaInAs quantum wells in 1989.[31] Soon after that, they realized a CW threshold current as low as 1.5 mA (CW) with a GaInAs single quantum well and a 5 μm square micropost structure.[32]

Geels and Coldren of the University of California, Santa Barbara reported a threshold current of 0.7 mA in a VCSEL with a strained InGaAs single-quantum-well active region.[33] This is the first report of a threshold current of less than 1 mA. Then, a sub-mA vertical-cavity surface-emitting laser with a 2.2 nm continuous tuning was demonstrated at Ulm University.[34] In 1993, Numai et al. of NEC reported a threshold current as low as 190 μA with a pulsed condition at room-temperature with an InGaAs/GaAs strained single-quantum-well active region and an air post structure of 5 μm.[35]

Deppe et al. of the University of Texas, Austin, achieved a room-temperature CW threshold current of 225 μA in a VCSEL with an InGaAs single-quantum-well active region.[36] The current was effectively confined by a 8 μm square native oxide aperture. The threshold current became as low as 91 μA by reducing the buried oxide aperture to 2 μm square.[36]

These results were followed by a 70 μA threshold current achieved by our group in 1995.[18] We employed an oxide AlAs/GaAs DBR to effectively confine the injection current and optical mode. A couple of months later, Yang et al. of the University of Southern California published a paper claiming the achievement of a threshold of 8.7 μA,[37] but this value has not been reproduced.

Besides the organizations described here, many others participated in the research on VCSELs and achieved low threshold currents of sub-mA, including the University of Ulm, the University of Würtzburg, Technical University of München, Technical University of Berlin, Sandia National Laboratories, Stanford University, and many corporations.[4]

5.4 Breakthrough innovations of VCSELs

Since the beginning of the 1990s, many research sectors have taken on the development of VCSELs and very low threshold devices reaching several μA have been reported. The turning points of the early stage of research are shown in Table II.

Since 1992, 850, 780, and 980 nm devices in lightwave systems have been commercialized. Aiming at exploring applications, 1300–1550-nm-wavelength, red-emitting AlGaInAs, and blue-emitting GaN devices are being developed as mostly cited in Ref. 4.

Our group has proposed some key concepts such as quantum-well VCSEL, multiquantum barrier (MQB), 1200 nm GaInAs/GaAs VCSEL, modulation schemes, phased-array VCSEL, Talbot-cavity VCSEL, tunneling injection, and tandem VCSEL.[4]

Also, high-efficiency and high-power VCSEL were developed to demonstrate a wall-plug efficiency >60%[38] and arrayed output power >1 kW.[39,40]

6. VCSEL applications in applied systems

6.1 Advantages of VCSELs and possible applications

With the progress of the device performance, the features of VCSELs, such as high productivity, high efficiency, low power consumption, a circular beam, a single frequency, and a two-dimensional array, are becoming well recognized by the society and their application areas have been expanding explosively since the mid 1990s. The application areas started from data communications followed by those of sensors, printers, and computer mouse pointers until the mid-2010s. After that, although the market size of data communication and sensing has grown steadily and is expected to grow further and occupy the main body of VCSEL and related markets, VCSELs are finding applications in new areas such as infrared illumination, pumping, and industrial heating.

Table II. Turning points in innovations of early stage of research (our group, unless otherwise specified).

1977. 03.22	The first concept in a laboratory notebook[1]
1978. 03.28	The first report of the 1977 idea[8]
1978.11	The 2nd report of the idea[9]
1979.09	Xerox patent, applied[29]
1980.01	Titech patent, applied[30]
1979.12	The first report on VCSEL oscillation[10]
1982.05	6-μm cavity length GaInAsP VCSEL[11]
1986.10	6-mA I_{th} GaAs VCSEL[15]
1988.07	GaAs/AlGaAs DBR VCSEL[25]
1988.09	Detailed characteristics of VCSEL[2]
1988.09	The first room-temperature CW[12,13]
1989.07	Jewell and others: Microlaser[31,32]
1990–95	Coldren, Ebeling, Deppe, Iga, and others: sub-mA I_{th}[18,32–37]
1992.08	Mechanical tuning of VCSEL demonstrated[27]
1995	Chang-Hasnain et al.: MEMS tunable VCSEL[28]

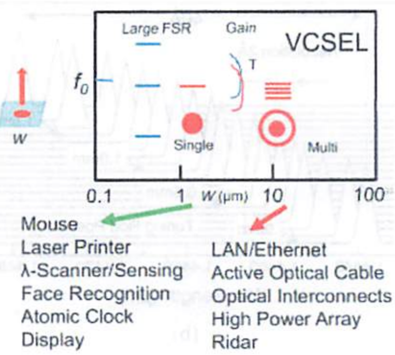


Fig. 7. (Color online) Single-mode vs multimode device categories and related applications.

In Fig. 7, we show the oscillation frequency versus diameter of VCSEL shown in Fig. 3. We distinguish the single-mode and multimode version of VCSELs, and their application areas. In the case of single-mode devices, we can achieve single transverse mode operation by reducing the diameter of the device to a few micrometers. A circular beam and single oscillation frequency can be obtained. On the other hand, in the case of multimode devices that have larger diameters, such as several microns or larger, we can attain high optical output and high-speed modulation capability.

From 1999, the VCSEL was applied to high-speed LANs, such as Gigabit Ethernet and its mass production started. To date, VCSELs have been applied to various IoT fields, as shown in Table II and Fig. 8. The market size of production is forecast to reach US$ 2,500 M in 2020.

6.2 Some commercial application areas

6.2.1 Tranceivers in Ethernet. Since around 1999, VCSELs started to be used in 1 Mbit/s Ethernet as light sources with graded-index multimode fibers.

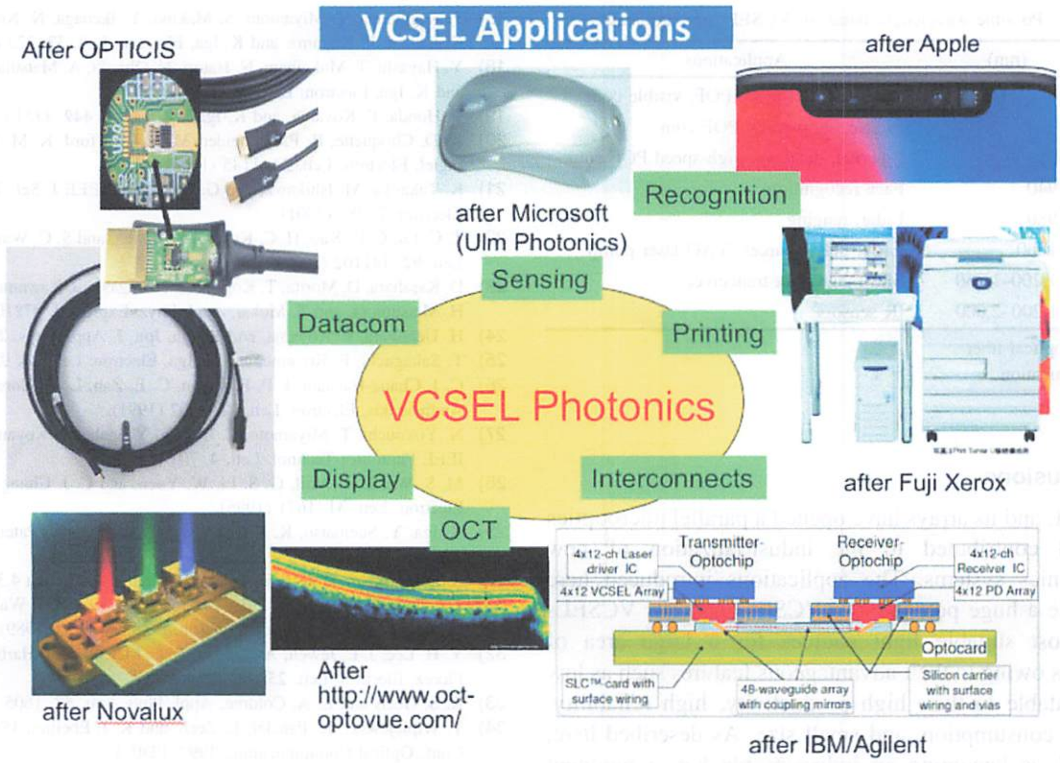


Fig. 8. (Color online) Some applications of VCSELs.

In response to the rapid growth of internet traffic, the expansion of the network bandwidth in a data center and between data centers was highly required. The standardization was promoted in a family of 100 Gbps Ethernet (100 GbE). Among them, 850 nm VCSELs are applied to SR10 in the standardization of datacom such as 100 GbEs.

6.2.2 Optical interconnects in data centers and super computers. The main market for VCSELs will be, in addition to communications, the intra- as well as inter-data centers and interconnects in high-performance computers and routers. For example, in the supercomputer Tsubame version 3.0 of Tokyo Institute of Technology, VCSEL transmitter-receivers were employed in 2017.[41] VCSEL has matured into a key component that supports the present and future networks and computers.

6.2.3 Laser printer. A laser printer is known as a high-quality and high-speed machine for digital printing markets. A conventional laser printer often uses a one-dimensional array of lasers/LEDs and performs scanning with a laser beam by rotating a polygon mirror. By replacing the single laser with a two-dimensional array of VCSELs, higher speed of printing became possible while improving the printing quality. For example, Fuji Xerox, developed a high-performance laser raster output scanner using 8×4 VCSEL arrays as an engine for the printing machine. A quality of 2,400 dpi was achieved with a printing speed of more than 100 sheets per minute.[42] Such high quality and high speed were realized by applying two-dimensional VCSEL arrays for the first time. Ricoh, followed by developing an array of 40 VCSELs.

6.2.4 Laser mouse. The first commercial application of VCSELs was the light source for the computer mouse that emerged in 2004. The numbers of shipped VCSELs are dominantly used for laser mice increased for some years since then. Owing to the circular output light beam with a small diameter from a single-mode VCSEL, higher tracking precision as well as lower electricity consumption is possible in VCSEL mice compared with conventional red-emitting LED mice.

Several companies such as Finisar Corporation and Philips ULM Photonics shipped 100 to 200 million VCSELs in 2013 and 2014. The total number of VCSELs shipped over the last 20 years is estimated to be nearly 1 billion.[39]

6.2.5 Face recognition. Today's smartphones are installed with many VCSELs, for example, for laser autofocus and proximity sensing by time-of-flight range detection and the face recognition. One of the smartphones, iPhoneX, recently put on sale is, said to have >500 pixels of VCSELs emitting at a 3 W peak power for face recognition.[40] The face recognition systems may be applied in security systems and for gesture recognition. A low-noise optical microphone is another application of VCSELs.

6.3 Further possible developments

We show the possible wavelength bands of VCSELs and applications in Table III. The naming of the 1300-nm-wavelength band "O" follows the expression for silica optical fibers. The others are tentatively named by myself for convenience.

After I retired from Tokyo Institute of Technology, many value-added technologies have been proposed by Koyama and his group, such as continuous tuning,[43] wavelength-temperature insensitivity (zero temperature coefficient),[43] MEMS integration, phased arrays, beam steering, high frequency modulation (>40 GHz),[44] and hollow-waveguide integration (modulator/slow light).

Table III. Possible wavelength bands of VCSELs and applications.

Band	(nm)	Applications
V	450–660	Display, short-reach POF, visible com
M	780	Mouse, short-reach POF com
Et	850	Ethernet, datacom, high-speed POF com
F	940	Face recognition
Li	980	Lidar, ranging
Ya	1060	LAN, SHG sources, YAG laser pump
O	1,200–1,360	Mid range fiber tranceivers
W	1,200–2,000	IR sensors

POF: plastic optical fiber
com: communication

7. Conclusions

The VCSEL and its arrays have opened a parallel microoptics world and contributed to the industrialization of new optoelectronics systems. The applications introduced here will provide a huge potential for VCSEL markets. VCSELs are the most suitable light sources for a large area of applications owing to their advantageous features such as low cost attributable to their high productivity, high reliability, low power consumption, and small size. As described here, the VCSEL is becoming an indispensable key component that supports the present and future information society from datacom to smart sensing.[45] It is not easy now to imagine a society without VCSELs.

Acknowledgments

I would like to express my deepest appreciation to Honorary Professor Yasuharu Suematsu for continuing advices. Also, I thank Professor Emeritus Kohroh Kobayashi for accumulating the data on VCSELs and on information on the VCSEL history, Professors Fumio Koyama, Tomoyuki Miyamoto, Hiroyuki Uenohara, and former laboratory members and students for collaboration.

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