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VCSEL Industry

Communication & Sensing

Babu Dayal Padullaparthi
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Dedication

With profound gratitude to all inspiring teachers, as well as scientists for the discoveries of light quanta, coherent photons, and engineered semiconductor laser devices, which are becoming blessing life-rays to humanity . . . to the Almighty (including late parents and current family) for providing an opportunity to see the brightness of invisible light in the darkest times of human tragedy . . . and to countless frontline medical staff, doctors, and law enforcement officials for selfless COVID-19 services to save this mighty planet.

Babu Dayal Padullaparthi

To my family, friends, and many co-workers that I have had the pleasure to work with and learn from over my lifetime. You have all been an inspiration to me. I especially thank my parents for the opportunities they afforded to me, and my daughter Destiny for being my best friend. Finally, to my mom, she is the strongest and most inspirational person I have ever known.

Jim A. Tatum

To my wife Tomoko for always supporting my research life and to my family, especially Soichiro, Hiroko, Saiko, and Yoichi for all the wonderful times we have spent together.

Kenichi Iga

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About the Book and Authors Biographies

This book on Vertical-Cavity Surface-Emitting Laser or VCSEL is targeted for young entrepreneurs, managers, engineers, and researchers in a wide range of industries to understand how VCSELs are used in communication and sensing. With increasing Internet traffic, and large-scale manufacturing in Consumer, Automotive, and Industrial sectors, VCSELs are in high demand and the forecasted market size exceeds $10B with more than 5B chips to be shipped over the next 10 years. The authors present an unique style of illustrations and practical engineering tenets to be easily understood by non-engineering readers.

- **Introductory chapters** convey a unique history of VCSEL by the inventor, plus fundamental operating characteristics and industrial landscape including market size, chip demand and manufacturing challenges through the use of a few example products.
- **Multi-mode VCSEL chapters** discuss applications of high-speed VCSELs in modern data centers and high-performance computing; short range 3D sensing in consumer devices including Face ID and autofocus functions for augmented reality; flash- and scan-based LiDARs for long distance ranging in the automotive industry; and illuminators in night vision, security systems, and industrial heating modules.
- **Single-mode VCSEL chapters** present multi-wavelength and MEMS tunable VCSELs for long wavelength communication, and sensing applications in optical mice, atomic clocks, laser printers, and optical coherence tomography (OCT) and the book concludes with a summary of present trend and future insight for VCSELs.
- **Several appendices** are included that cover VCSEL design, epi-structure growth, wafer fab, testing, reliability, eye-safety, visible wavelength VCSEL applications, and photodetectors to serve as supplements to the main chapters.



Babu Dayal PADULLAPARTHI received his B. Sc./M. Sc., M. Phil., Ph. D. degrees from Andhra University (Govt. College at Rajahmundry), University of Hyderabad, IIT Delhi, all in Physics in 1994/1997, 1999, 2005, respectively. Dr. Padullaparthi worked in Tokyo Institute of Technology on VCSELs during 2005-09. Dr. Padullaparthi founded Photonic Components DFM Ltd., HK in 2017 to offer professional services in Datacom, 3D Sensing and LiDAR areas. He held many senior executive roles in HK and PRC companies in promoting multiple high volume VCSEL development & manufacturing projects. He received the Outstanding Poster Award from MRS in Fall 2004, JSPS Post-Doctoral Fellowship in 2005, and IEEE LEOS i-NOW / Japan Chapter Young Scientist Award in 2008. Dr. Padullaparthi has co-authored more than 50 peer reviewed technical papers on photonic materials and devices, is the co-inventor of 24 patents, and a member of IEEE (Photonics and Communications Societies), Optica (formerly OSA) & SPIE.



Jim TATUM received a BA from Austin College, and MS and PhD in electrical engineering from the University of Texas at Dallas. Dr. Tatum joined Honeywell in 1996 as a design engineer and was instrumental in the introduction of the world's first commercial VCSEL products. He later held roles in strategic marketing and finally as director of new product development at Finisar. Under his leadership, VCSELs operating at speeds up to 28Gbps were developed along with commercialization of single mode polarization locked VCSELs and high power VCSEL arrays for 3D sensing. More than 300M VCSELs based on his team's efforts are operating in the field today. In 2018 Dr. Tatum founded Dallas Quantum Devices and continues to develop even higher speed VCSELs along with a variety of VCSEL solutions in corollary sensor markets. Dr. Tatum has been granted more than 50 patents and authored many technical publications on VCSELs and related applications.



Kenichi IGA received his B. E., M. E., and Dr. Eng. Degrees from Tokyo Institute of Technology in 1963, 1965 and 1968, respectively. He joined Tokyo Institute of Technology in 1968, becoming Associate Professor in 1974, and Professor in 1984. In 2001 he was awarded Professor Emeritus. He served as the 27th President of Tokyo Institute of Technology for 2007–2012. From 1979 to 1980, he worked at Bell Labs., Holmdel. Professor Iga initiated pioneering research programs in surface emitting laser (VCSEL) and microoptics. He received 1992 IEEE/LEOS William Streifer Award, 1998 IEEE/OSA John Tyndall Award, 2003 IEEE Daniel E. Noble Award, 2002 Rank Prize, 2013 Franklin Medal with the Bower Award and Prize, and 2021 IEEE Edison Medal. He plays a contrabass as a hobby.

Foreword

"A conventional stripe semiconductor laser consists of two end mirrors perpendicular to the active layer so that the light output is parallel to the wafer surface. If a semiconductor laser with the light output perpendicular to the wafer surface could be obtained, it would be very easy to fabricate a 2-dimensional laser array. . ." This was proposed by Kenichi Iga in 1977, and the first paper on its realization, written by Haruhisa Soda, Kenichi Iga, Chiyuki Kitahara, and Yasuharu Suematsu, came out in 1979 [1]. This paper was a key milestone for the birth of the vertical-cavity surface-emitting laser, or VCSEL, as we now call it. As a longtime worker in fiber optics communications, I realize that the geometry of "the conventional laser" was deeply ingrained in the mindset of system engineers. The design, alignment, and packaging of an end-to-end fiber optics system were by and large catered to the concept that the laser light output is parallel to the wafer surface.

Following breakthroughs of the first room-temperature CW operation of VCSELs [2] and the first experimental demonstration of a 2D VCSEL array [3], worldwide VCSEL R&D was kick-started in the early 1990s. In 2000, DARPA managers Elias Towe, Robert F. Leheny, and Andrew Yang wrote the following about VCSEL in their review paper [4]: "Its size, manufacturability, and potential ease of heterogeneous integration of electronics promise a range of applications that have yet to be explored." This was the time DARPA invested considerable human and monetary resources in the R&D of VCSELs, in particular the massive integration of VCSELs, detectors, micro-optics, and driving electronics for optical backplanes, free-space optical interconnections, and all optical switching. While these applications did not emerge immediately, the DARPA funding impetus did drive widespread commercialization efforts.

The first commercial VCSELs, offered by Honeywell in 1996, were driven by the emerging demand for global bandwidth [5] that is now fueled by the need for low-cost data center communications with the worldwide construction of giant data centers by cloud computing companies such as Google, Amazon AWS, Facebook, and Alibaba. First generation VCSELs operated at 1 Gbps and have since evolved to datalink or active optical cables operating at 25 Gb/s NRZ modulation and 50 Gb/s PAM4 modulation for a single channel. Spectral and spatial multiplexing results in bandwidth expansions from 25 Gb/s to more than 400 Gb/s optical networks using multiple channels over a distance of several hundred meters. Another application in optical communications is in the widespread deployment of radio access network (RAN) in 4G and 5G LTE wireless fronthaul networks.

Yet another impetus for VCSEL applications is the progress in optical sensing and imaging in the fields of consumer electronics (mobile/smartphones) and automotive transport (autonomous vehicles through LiDARs). The property of optical signal processing perpendicular, rather than parallel, to the wafer surface makes VCSEL an ideal light source for many applications in computer vision and sensing. In 2017, Apple Inc. began to incorporate several kinds of VCSELs into its latest products starting with a structured light source for 3D depth sensing application (face ID) and now

includes a LiDAR with 5 m range. We also witnessed the introduction of massively integrated VCSELs in other commercial LiDARs that has the potential to address the question of scalability in increasing the number of laser scanning lines beyond 16 and 32 to 64, 128, or even higher. The ability to integrate a large number of parallel beams perpendicular to the surface of the wafer also makes a VCSEL structure ideal for high-power (kW level) applications such as laser heating and laser cutting, among others. Other multi-mode and single-mode applications for VCSELs include atomic clocks, computer mice, laser printers, biometrics (Optical Coherence Tomography OCT), defense (drones), gas sensing, and polarization-controlled light sources for future quantum communication. Over the past 40 years, VCSELs have moved from a research curiosity to more than one billion devices in use today in a diverse range of applications. This commercial ramp-up has attracted a large commercial base that has heavily invested in high-volume manufacturing infrastructure [6].

With VCSELs now representing a multibillion-dollar global industry and worldwide interest in VCSEL's commercial usage, it is timely to write a book covering these wide range of applications and help to stimulate other novel applications. We are very fortunate and deeply honored to have Dr. Babu Dayal Padullaparthi, Dr. Jim Tatum, and Professor Kenichi Iga, a team of VCSEL experts who kindly agreed to write the book for Wiley-IEEE Press. Professor Iga is none other than the original VCSEL pioneer and author of the 1979 paper mentioned earlier. These three outstanding researchers have a collective amount of experience in academic and industrial research as well as commercial productization of VCSEL spanning the past four decades. They will provide the readers with a historical perspective and current state-of-the-art technology and product status of the field. Through the authors' extensive contacts with leading VCSEL manufacturers worldwide, the book will also present an up-to-date picture of R&D and product trends for both researchers and practicing engineers. I am confident that the readers will find this book an enjoyable tutorial and product reference covering the long and exciting journey of VCSELs.

Nim Cheung
Series Editor, Wiley-IEEE Press
November 23, 2020

References

1 H. Soda, K. Iga, C. Kitahara, and Y. Suematsu, 'GaInAsP/InP surface emitting injection lasers', *Jpn. J. App. Phys.*, Vol. **18**, No. 12, Pages 2329–2330 (1979)

2 F. Koyama, S. Kinoshita and K. Iga, 'Room temperature CW operation of GaAs vertical cavity surface emitting laser', *IEICE Trans.*, **E71**, 1089–1090 (1988)

3 Y. H. Lee, J. L. Jewell, A. Scherer et al., 'Room-Tempreature, Continuous-Wave Vertical-Cavity Single-Quantum-Well Microlaser Diodes', Electronics Letters **25**, No. 20 Pages 1377–1378 (1989)

4 E. Towe, R. F. Leheny, and A. Yang, 'A historical perspective of the development of the vertical-cavity surface-emitting laser', *IEEE J. Sel. Top Quantum Electron.*, Vol. **6**, No. 6, Pages 1458–1464 (2000)

5 J. A. Tatum, A. Clark, J. K. Guenter, R. A. Hawthorne, and R. H. Johnson, 'Commercialization of Honeywell's VCSEL technology,' *Proc. SPIE* **3946** 2–13 (2000)

6 B. D. Padullaparthi, R. Chen, A. Tan et al. 'High Volume Manufacturing of VCSELs for Datacom & Sensing', Industry Panel Discussions, Th4, pp: 51, International Nano-Optoelectronics Workshop (i-NOW) 2018, UC Berkeley, USA.

Preface

A vertical-cavity surface-emitting laser (VCSEL) is experiencing rapid growth followed by applications mostly in communication and sensing. This book describes the industrial technologies driven by the rapid expansion of the information age and the extension into rapidly emerging areas of AI (artificial intelligence) and IoT (Internet of Things).

The VCSEL was first conceived in 1977 by Kenichi Iga, one of the authors and while the device itself is smaller than a sesame seed, its impact on the world is profound. The unique advantages of small size, surface normal emission, and scalability into 1D and 2D arrays are hallmarks of the device. The name VCSEL was chosen because the light is emitted perpendicular to the wafer, and the pronunciation as "viksel" is reminiscent of a pixel in the scalability into large 2D structures.

Iga has continued basic research on VCSELs ever since its invention and witnessed commercialization in 1996 as the Internet began its rapid expansion. The first VCSEL products were in optical transceivers used in data centers, which support the modern information age. Along with the spread of the Internet, information-related companies now own huge information storage centers called the cloud (a mechanism for storing information in memory, such as hard disks, to read and use it). High-speed optical fiber networks exchange large volumes of information to and from data centers. Each of these data centers may contain many hundreds of thousands of VCSEL-based optical interconnects. In fact, VCSELs today provide more than 50 Mbps of connectivity for every person on earth.

In addition, many computer users have a mouse, which uses an optical source and a camera to track its position movement. The number of units produced so far is more than 1.1 billion. In 2017, the VCSEL was also adopted by the iPhone X for facial recognition. More recently, a laser RADAR (LiDAR) is being implemented in smartphones and iPads to enable AI and augmented reality. A new era of optical sensing was born taking advantage of the VCSEL's small volume, low power consumption, and scalability.

It can be said that most of us are using VCSELs even without recognizing them. This small device is becoming a powerful tool that supports the flow of information in everyday life.

The current technological progress has caused many paradigm-shifts in the information communication world, and we look at the new world of optoelectronics centering on VCSELs because they will be firmly rooted as the devices that enable the IoT and AI smarter. As for the descriptions of the theory and mechanism of the laser, we discuss the VCSEL from the industrial point of view in this book.

Applications of surface-emitting lasers are expanding, and the numbers of researchers, developers, and manufacturers who handle them are also increasing. The book is intended for a broader

audience in industry and introduces the basic ideas and the scope of applications that have not necessarily been written in most of academic papers and textbooks.

We would be extremely pleased if this book could serve as an opening gate for emerging new VCSEL industries.



Kenichi Iga
Tokyo, Japan
July 11, 2021

Introduction

VCSEL, or vertical-cavity surface-emitting laser is now a buzzword in the science and engineering community. The excitement is driven by the promise of 3D applications everywhere, including smart phones, cars, gaming, and other forms of augmented or virtual reality. The new era for VCSELs was ushered in with the introduction of face recognition technology in the iPhone X. Since commercial introduction in 1996, VCSELs have long been the workhorse of data communication and data centers. As global Internet connectivity has grown, so has the VCSEL industry, expanded from producing a few tens of 75 mm wafers per year to thousands of 150 mm wafers today. Speeds have grown from 1 Gbps to over 56 Gbps in commercial data center products. VCSELs also found success in optical mice, autofocus assist, atomic clocks, and many other applications. But all of these taken together still did not drive interest of large-scale industrial production that consumer electronics could demand. In fact, despite the success of VCSELs, it was still considered a cottage industry until just a few years ago. One of the key advantages of VCSELs—small size—was limiting the wafer volume production to small boutique fabs. Early applications did not take advantage of another key attribute of VCSELs, scalability into 2D arrays of emitters. The typical VCSEL die used in a 3D sensing application is more than 20x the size of one used in data communications! This scaling of chip size and market opportunity has caused a huge surge in VCSEL wafer demand. Today high-volume applications in the consumer, automotive, and industrial sectors have driven VCSELs to become a multi-billion-dollar market, and that excludes traditional datacom and data center interconnects. With all of the activity around VCSELs, several engineering textbooks and references of VCSEL technology have been written, but none has focused on the basic operating principles, and none included aspects of manufacturing challenges and market dynamics.

This book is targeted to young entrepreneurs, managers, engineers, and researchers in a wide range of industries to understand how VCSELs are used in high-volume communication and sensing applications, to identify key manufacturing challenges, and future market prospects. In contrast to traditional academic textbooks, the technical content is focused on engineering design and the application of VCSELs with few mathematical expressions. The authors use a unique style of illustrations and practical engineering tenets to describe VCSEL operating principles and how they are used in a variety of applications. The book is a collection of experiences and the authors' views on topics that have and will drive the continued expansion of the VCSEL market. In other words, the book gives clear insight to understanding the overall landscape of the VCSEL industry and helps readers access the risks and rewards of the many segments. Readers are introduced to the basic operating principles of VCSELs that are relevant to application design, and a specific background in semiconductor lasers is not necessarily required. The book is focused on engineering understanding and industrial production of VCSELs and their applications. We are proud to include the historical perspectives and future insight in this book from Professor Kenichi Iga, the inventor of the VCSEL, and the 50th anniversary of the birth of VCSEL on March 22, 2027!

Chapter 1 introduces the history of semiconductor lasers, in particular VCSELs, and the potential of VCSELs as major components of choice in photonic applications. **Chapter 2** describes the basic structure of a VCSEL and its fundamental operating characteristics. **Chapter 3** describes the landscape of the VCSEL industry including leading participants, market size, chip demand, manufacturing challenges, and a few commercial products as examples. **Chapter 4** deals with the high-speed multi-mode VCSELs for datacom applications and its potential for 100G and 400G networks. **Chapter 5** focuses on multi-mode VCSEL arrays for short-range 3D sensing (up to 10 m) applications including proximity sensing in automobiles, autofocus functions for augmented reality, and facial recognition. **Chapter 6** considers multi-mode VCSEL array chips as light sources for flash- and scan-based LiDARs for long-distance ranging (up to 250 m) in the automotive industry. **Chapter 7** describes multi-mode VCSEL-based illuminators in night vision and security systems and continues the scaling of VCSELs to kW levels used in industrial heating modules. **Chapter 8** focuses on single-mode VCSELs for sensing applications, and **Chapter 9** deals with single-mode communications applications that will be the starting point for single- and entangled-photon sources for many quantum applications. **Chapter 10** summarizes the present trends and provides insight into the future directions for VCSELs and their impact on commercial products. The authors also provide several topics that are closely connected to the aforementioned chapters and cover some of the other considerations of VCSEL industrial production as **appendices**. These include design, epi-structure growth, wafer fab, testing, reliability, eye-safety, short (GaN and display), and visible-wavelength VCSEL applications, as well as photodetectors.

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Hong Kong, July 31, 2021

Jim Tatum
Celina, Texas/USA, July 30, 2021

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The authors would also like to thank the many co-workers, students, and colleagues that we have worked with over the years. We have learned a lot about VCSELs and especially have learned that these are one of the most complicated two-terminal devices ever manufactured. Writing this book has reinforced the breadth and depth of understanding needed in multi-disciplinary physics to design and manufacture VCSELs. They encompass aspects of mechanical, electrical, thermal, optical and solid-state physics are truly remarkable devices. Along with the technical challenges, the realization of market forces, the drive of standardization, and the necessity of meeting commercial objectives have been an amazing journey for all of us. The advances in so many interdisciplinary aspects of engineering have enabled more than 1 billion devices manufactured since its invention in 1977.

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