A New VCSEL Book

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After about nine years of lean times, in the year 2012 there will be a new book on the market that is entirely devoted to vertical-cavity surface-emitting lasers (VCSELs). The present article briefly introduces the contents of this edited volume.

1. Introduction

Six books written in English with an exclusive focus on VCSELs have been published during the years 1995–2003 [1–6]. Enormous progress of VCSEL performance and applications has been achieved since then. In 2012 Springer-Verlag will thus publish a new VCSEL book [7] which will be a multi-author volume containing 18 chapters and about 550 pages. Figure 1 shows its tentative cover. Some of the chapters are state-of-the-art updates of chapters in previous VCSEL books. In addition, entirely new contributions are made to the fields of vectorial three-dimensional optical modeling, single-mode VCSELs,

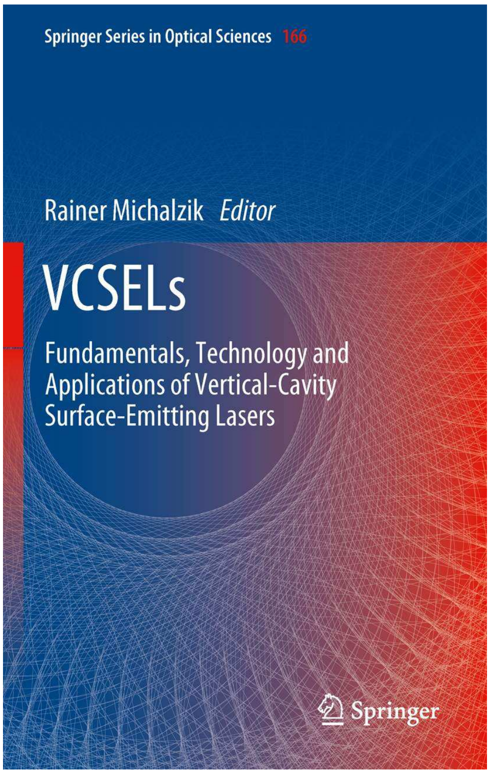

Fig. 1: Tentative cover design of the VCSEL book.

polarization control, polarization dynamics, very-high-speed design, high-power emission, use of high-contrast gratings, GaInNAsSb long-wavelength VCSELs, optical video links, VCSELs for optical mice and sensing, as well as VCSEL-based laser printing.

2. VCSEL Book Chapters

To give an overview of the contents of the book, in what follows we will introduce the individual book chapters in terms of their titles and abstracts with the authors and their affiliations inserted in square brackets.

1. **VCSELs: A Research Review** [R. Michalzik, Ulm University, Germany]: This chapter attempts to briefly review the research history of vertical-cavity surface-emitting lasers (VCSELs). Based on the contents of previous monographs on VCSELs written in English, we motivate the selection of topics in the present book and give an introduction to the individual chapters. Moreover, we mention some other research that is not covered in a dedicated chapter in order to provide the readers with even deeper insights into VCSEL research. Future directions and opportunities are also indicated.

2. **VCSEL Fundamentals** [R. Michalzik, Ulm University, Germany]: In this chapter we outline major principles of vertical-cavity surface-emitting laser (VCSEL) design and operation. Basic device properties and generally applicable cavity design rules are introduced. Characteristic parameters like threshold gain and current, differential quantum efficiency and power conversion efficiency, as well as thermal resistance are discussed. We describe the design of Bragg reflectors and explain the transfer matrix method as a convenient tool to compute VCSEL resonator properties in a one-dimensional approximation. Experimental results illustrate the emission characteristics of high-efficiency VCSELs that apply selective oxidation for current and photon confinement. Both the 850 and 980 nm wavelength regions are considered. The basic treatment of laser dynamics and noise behavior is presented in terms of the small-signal modulation response as well as the relative intensity noise. Finally we give some examples of VCSEL applications in fiber-based optical interconnects, i.e., optical data transmission over short distances.

3. **Three-Dimensional Modeling of VCSELs** [P. Debernardi, IEIIT-CNR, Torino, Italy]: VCSELs are complicated objects, also from a modeling point of view. In fact the computation of statical and dynamical operation implies the interaction of different physical phenomena: electrical, thermal and optical. All are strongly coupled and rule device operation. In this chapter the relevant effects and corresponding mutual interactions will be reviewed and possible ways to numerically address them discussed. Particular attention will be devoted to the optical solver, which is the core of any VCSEL simulation tool. In fact the optical characteristics determine the final device performance.

4. **Single-Mode VCSELs** [A. Larsson, J.S. Gustavsson, Chalmers University of Technology, Sweden]: The only active transverse mode in a truly single-mode VCSEL

is the fundamental mode with a near Gaussian field distribution. A single-mode VCSEL produces a light beam of higher spectral purity, higher degree of coherence and lower divergence than a multimode VCSEL and the beam can be more precisely shaped and focused to a smaller spot. Such beam properties are required in many applications. In this chapter, after discussing applications of single-mode VCSELs, we introduce the basics of fields and modes in VCSELs and review designs implemented for single-mode emission from VCSELs in different materials and at different wavelengths. This includes VCSELs that are inherently single-mode as well as inherently multimode VCSELs where higher-order modes are suppressed by mode selective gain or loss. In each case we present the current state-of-the-art and discuss pros and cons. At the end, a specific example with experimental results is provided and, as a summary, the most promising designs based on current technologies are identified.

5. **Polarization Control of VCSELs** [J.M. Ostermann, R. Michalzik, Ulm University, Germany]: In most types of VCSELs, the light output polarization is inherently unstable. While, in case of single-mode oscillation, the emitted light is mainly linearly polarized, its orientation is not well defined. This is because both the resonator and the gain medium are quasi isotropic in the plane of the active layers. Since a stable polarization is required for almost all sensing and some datacom applications, extensive and in-depth investigations have been undertaken during the last twenty years in order to stabilize the polarization of VCSELs without affecting their favorable operation parameters. Polarization control of VCSELs can be achieved by introducing a polarization-dependent gain, an asymmetric resonator, or mirrors with a polarization-dependent reflectivity. It has turned out that the last approach is most promising. It can be realized by incorporating a shallow surface grating in the upper mirror of a top-emitting VCSEL. Several million grating VCSELs are in reliable operation meanwhile, mainly in optical computer mice.

6. **Polarization Dynamics of VCSELs** [K. Panajotov, Vrije Universiteit Brussel, Belgium, F. Prati, Università dell'Insubria, Italy]: In this chapter we wrap up the experimental and theoretical results on polarization dynamics of solitary vertical-cavity surface-emitting lasers. Experiments have shown that VCSELs emit a linearly polarized fundamental transverse mode either along the [110] or [1$\bar{1}$0] crystallographic direction. Polarization switching between these modes can occur when the injection current is increased, showing either a frequency shift from the higher to the lower frequency mode (type I) or the reverse (type II). The two modes of linear polarization are strongly anti-correlated. The switching can happen through a region of mode hopping, with a dwell time scaling over eight orders of magnitude with the switching current, or through a region of hysteresis. Thermal (carrier) effects influence the polarization behavior of VCSELs through a red (blue) shift of the gain maximum. Also, in-plane anisotropic strain can strongly modify the polarization behavior of VCSELs. All these experimental results call for explanations, as there is no a priori intrinsic polarization selection mechanism in VCSELs. We present different gain equalization models to explain type I, type II or double polarization switching. Alternatively, the spin-flip model can explain both types polarization

switching by involving a microscopic spin-flip relaxation mechanism. Its predictive power has been experimentally established as, e.g., polarization switching through elliptically polarized states and dynamical instabilities. Finally, we highlight some perspective applications using polarization dynamics of VCSELs.

7. **Design and Performance of High-Speed VCSELs** [Y.-C. Chang, L.A. Coldren, University of California, Santa Barbara, USA]: Over the past several years, high-speed vertical-cavity surface-emitting lasers (VCSELs) have been the subject of intensive worldwide research due to their applications in optical interconnects and optical data networks. The performance of VCSELs, especially with respect to their high-speed characteristics, has made significant progress. In this chapter, we first present the basic theory for current-modulated VCSELs using rate equations and small-signal analysis. Factors that affect the modulation bandwidth, including the intrinsic laser responses and extrinsic parasitics, are identified. Once these limitations are known, we discuss various designs that have been implemented in VCSELs to specifically address them, followed by a review of the current high-speed VCSEL performance based on these designs at several different wavelengths, including 850 nm, 980 nm, 1.1 μm, and 1.3–1.6 μm. Finally, we consider new modulation schemes based on loss modulation in coupled-cavity VCSELs, which has the potential to reach even higher speeds.

8. **High-Power VCSEL Arrays** [J.-F. P. Seurin, Princeton Optronics, USA]: We review recent developments on high-power, high-efficiency two-dimensional vertical-cavity surface-emitting laser (VCSEL) arrays emitting around 808 and 980 nm. Selectively oxidized, bottom-emitting single VCSEL emitters with 50 % power conversion efficiency were developed as the basic building block of these arrays. More than 230 W of continuous-wave (CW) power is demonstrated from a 5 mm × 5 mm array chip. In quasi-CW mode, smaller array chips exhibit 100 W output power, corresponding to more than 3.5 kW/cm^2 of power-density. High-brightness VCSEL pumps have been developed, delivering a fiber output power of 40 W, corresponding to a brightness close to 50 $kW/(cm^2\,sr)$. High-energy VCSEL arrays in the milli-Joule range have also been developed. Many of the advantages of low-power single VCSEL devices such as reliability, wavelength stability, low-divergence circular beam, and low-cost manufacturing are preserved for these high-power arrays. VCSELs thus offer an attractive alternative to the dominant edge-emitter technology for many applications requiring compact high-power laser sources.

9. **High-Contrast Grating VCSELs** [C.J. Chang-Hasnain, University of California, Berkeley, USA]: We review a recent invention of single-layer one-dimensional high-index contrast subwavelength grating (HCG) and its incorporation into a VCSEL structure. The HCG is approximately 50 times thinner than a conventional distributed Bragg reflector (DBR), but offers higher reflectivity with a much broader spectral width. It provides lithographically defined control of polarization, transverse mode and emission wavelength. Using this ultrathin reflector, the tunable mirror in a micromechanical HCG-VCSELs are fabricated with a 10^4 times volume reduction and more than two orders of magnitude improved tuning speed.

10. **Long-Wavelength VCSELs With Buried Tunnel Junction** [M. Ortsiefer, VERTILAS, Germany, W. Hofmann, Technische Universität Berlin, Germany, J. Rosskopf, VERTILAS, Germany, M.-C. Amann, Technische Universität München, Germany]: Despite the earliest work on VCSELs in the late 1970s on InP-based materials, the further realization of VCSELs beyond 1.3 µm emission wavelength has been significantly delayed for many years with respect to their short-wavelength counterparts on GaAs substrates. This chapter covers the specific challenges, solutions and application prospects of VCSELs in non-GaAs-based material systems which are suitable for achieving significantly extended wavelength ranges. By using highly advanced device concepts, since the late 1990s it became possible to overcome the fundamental technological drawbacks related with long-wavelength VCSELs such as inferior thermal properties and to realize lasers with remarkable device performance. In particular and with respect to huge application opportunities in optical communications, this chapter presents InP-based VCSELs with single-mode output powers of several milliwatts at room temperature and well beyond 1 mW at 85°C, as well as modulation frequencies far above 10 GHz in conjunction with ultra-small power consumption. While the InP-based VCSEL technology is limited to maximum emission wavelengths around 2.3 µm, even longer emission up to the mid-infrared wavelength range can be achieved with VCSELs based on GaSb. With their inherent and, compared to other laser types, superior properties like enhanced tuning characteristics, long-wavelength VCSELs are regarded as key components for applications in optical sensing.

11. **GaInNAs(Sb) Long-Wavelength VCSELs** [J.S. Harris, H. Bae, T. Sarmiento, Stanford University, USA]: The push to provide high-speed optical network access directly to the end user is creating both significant pressure for the development of low-cost, high-speed access terminals as well as opportunities for development of entirely new technological approaches compared to those now used in the optical backbone networks. One of the most challenging is that of providing low-cost, long wavelength, single mode lasers that can be directly modulated at 10 Gbit/s, operate un-cooled in ambient environments and are easily packaged and coupled to fiber. Long wavelength vertical cavity surface emitting lasers (VCSELs) on GaAs certainly have the potential to meet these challenges. The development of MBE growth of GaInNAsSb on GaAs, issues of VCSEL design and successful demonstration of low threshold edge emitting lasers and the first 1530 nm monolithic VCSELs in GaInNAsSb on GaAs are described.

12. **Red Emitting VCSEL** [M. Jetter, R. Roßbach, P. Michler, Universität Stuttgart, Germany]: This chapter describes the progress in development of vertical-cavity surface-emitting lasers (VCSEL) emitting in the red spectral region around 650 nm for data transmission over polymer optical fibers (POF). First, growth issues of red VCSEL using two different material systems, namely AlGaAs and AlGaInP, are introduced. In particular, the optical and electrical state-of-the-art characteristics as low threshold currents (1 mA) and high output powers (several mW) are presented with a special focus on emission wavelength. Also the thermal budget and heat removal in the devices are pointed out with regard to the geometry of the VCSEL.

Small-signal modulation response in terms of maximum resonance frequency in dependance on temperature behavior are discussed. Applications of these devices in optical interconnects are described and digital data transmission at data rates up to 2.1 Gbit/s over step-index POF is reported. These properties make red emitting VCSEL perfectly suited for high-speed low power consuming light sources for optical data communication via POF. By introducing InP quantum dots as gain material in red emitting VCSEL nearly temperature independent record low threshold current densities of around 10 A/cm^2 could be observed.

13. **GaN-Based VCSELs** [S.-C. Wang, T.-C. Lu, H.-C. Kuo, J.-R. Chen, National Chiao Tung University, Taiwan]: This chapter first briefly reviews the background of the development of GaN-based edge-emitting lasers and key technical issues and approaches. Then we present the design considerations and fabrication technology for the development of GaN-based vertical-cavity surface-emitting lasers (VCSELs). The technical issues and approaches for fabricating high-quality and high-reflectivity GaN distributed Bragg reflectors (DBRs) are discussed. The trade-offs among the three kinds of GaN microcavity structures are compared. Fabrication processes and key performance characteristics of hybrid and double dielectric microcavities for optically pumped GaN VCSELs are presented. The key approaches to achieve electrically pumped GaN VCSELs are analyzed and recent developments in electrically pumped GaN VCSELs are described. The future prospects of enhancing the GaN VCSEL performance and operation temperature are discussed. Finally the emerging applications for nitride-based VCSELs are briefly described.

14. **VCSEL-Based Transceivers for Data Communications** [K.P. Jackson, Emcore, USA, C.L. Schow, IBM, USA]: The data communications (datacom) transceiver market has experienced tremendous growth over the last fifteen years due in large part to the use of vertical-cavity surface-emitting lasers (VCSELs) and multimode optical fibers. This chapter reviews the evolution of 850 nm laser-based datacom transceivers beginning with the early use of AlGaAs edge-emitters to the adoption of VCSELs where their unique attributes have enabled significant performance enhancements and cost reductions in transceiver designs.

15. **Low-Cost Optical Video Links Based on VCSELs** [H.-K. Shin, OPTICIS, Korea]: The history of introduction and current status of VCSEL based optical video link modules which have emerged as one of the main applications of VCSELs are described. The structure and characteristics of VCSELs in optical video links are summarized. The technical issues of the next generation optical video links for the mass market are discussed.

16. **Progress in VCSEL-Based Parallel Links** [D.M. Kuchta, IBM, USA]: This chapter covers most aspects of VCSEL-based parallel optical links during the period of 2000–2010, a period of tremendous advancement in this field both in research and in commercial deployment. Section 16.1 introduces the topic. Commercial activities are covered in Sect. 16.2. Section 16.3 covers research activities in this field. Deployment of these technologies in large systems, supercomputers and test

beds is discussed in Sect. 16.4. Advances in multi-fiber, multicore fiber and multi-fiber connectors for parallel links is the topic of Sect. 16.5. Section 16.6 discusses reliability for parallel links and its application to large systems. Finally, Sect. 16.7 concludes the chapter with future applications for VCSEL-based parallel links.

17. **VCSELs for Optical Mice and Sensing** [M. Grabherr, Philips Technologie GmbH U-L-M Photonics, Germany, H. Moench, Philips Research Laboratories, Germany, A. Pruijmboom, Philips Laser Lighting Systems, The Netherlands]: A real mass application for VCSELs is their use in optical mice and sensing. As illumination source for sensing applications VCSELs offer a better performance than LEDs. The even more advanced approach of laser self-mixing interference sensors allows a next step in integration, accuracy and new application fields. This chapter summarizes the major requirements towards VCSELs in illumination for sensing applications and gives typical specifications. A detailed description of the production process and the achieved reproducibility makes clear that these VCSELs are ideally suited for production in large quantities. In the second half of the chapter the self-mixing interference method is described in more detail and a highly integrated two axes laser Doppler interferometer is shown. This product is designed for a laser mouse but offers a number of other sensing applications.

18. **VCSEL-Based Laser Printing System** [N. Ueki, N. Mukoyama, FUJI XEROX, Japan]: There is an endless demand for improved image quality and higher speed in printer applications. To meet market requirements, in 2003 we launched DocuColor 1256GA, the world's first VCSEL-based electrophotographic printer utilizing a 780 nm single-mode 8×4 VCSEL array. The printer features 2400 dots per inch (dpi) resolution, which is still the highest level in the industry, and a speed of 12.5 pages per minute (ppm). A two-dimensional VCSEL array makes it much easier to increase the pixel density and printing speed by simultaneously scanning the 32 beams on the photoconductor in the light exposure system. Adopting VCSELs as a light source also contributes to reduced power consumption, because the operating current of VCSELs is extremely small and the wall-plug efficiency is very high. In this chapter, we explain the key technologies of VCSELs in light exposure system of laser printer, as well as their required characteristics to assure high image quality.

3. Conclusion

The time was ripe for a new VCSEL book. With this volume we hope to have closed the gap — at least for a little while.

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