

THREE-DIMENSIONAL SIMULATION
OF VERTICAL-CAVITY
SURFACE-EMITTING LASERS

PH.D. THESES

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Introduction

Vertical-cavity surface-emitting lasers (VCSELs) were invented by K. Iga in 1977. One can recognize three stages of the research and development of these devices. It was proved in the first decade that room temperature operation was feasible to achieve. Low threshold current and good power efficiency were demonstrated in the nineties by employing new structural components, such as an oxide aperture that confines both the current and the optical modes. Having reached, or in some cases exceeded the typical characteristics of edge-emitting lasers, the industrial interest was increased. Longer wavelength VCSELs aiming single-mode optical communication, and also devices in the visible region for displaying purposes are being nowadays rapidly developed, besides the conventional multi-mode devices that radiate at 850 nm. Single-mode, single-polarization lasers incorporating special surface reliefs or photonic crystals (PhC) are recently in the focus of academic research.

Although the industrial development follows mainly an experimental procedure, several methods were published for the theoretical understanding of VCSELs. These are often grouped as electric, thermal and optical models according to the investigated phenomena. While the optoelectronic interaction determines the intensity of the laser modes on the fast time scale, it is a reasonable approximation to consider quasistationary mode profiles, which depend on the built-in refractivity distribution. As VCSELs usually possess a complicated structure, and they are inherently open resonators from which light is emitted, the calculation of the optical fields inside the device is not straightforward. Although there exist approximate analytical solutions for axisymmetric cases, such as the weighted index method, they cannot be used for modern, advanced devices.

Only coupled mode model proved successfully previously for the optical simulation of general noncylindrical VCSELs. It had been derived first to study the effects of imperfections in optical fibers. This approach demands only moderate computer resources, but is inexact from a mathematical point of view, as it prescribes continuous variation of all electric

field components irrespective of the discontinuity of the refractive index at material interfaces. Finite element modeling could eliminate this unphysical feature, but its implementation for general three-dimensional lasers was rejected few years ago due to the dissatisfactory computer resources. Nevertheless, axisymmetric geometries were modeled in this numerical way.

Goals

I intended to develop optical models that are appropriate for the simulation of arbitrary index-guided VCSELs. These are created either unintentionally due special growth conditions, or designed systematically. Fast approximate methods, as well as sophisticated high-precision numerical approaches were searched according to the hierarchical modeling concept. Since huge computer resources were expected for fully three-dimensional calculations, I also investigated efficient numerical algorithms to reduce the demands to a moderate level.

It was a natural requirement to couple the resonator mode calculation to electronic and thermal processes. A unified discretization scheme is preferred for the sake of an easier mathematical treatment. The rigorous multilayer structure and the curved lateral contours of typical VCSELs legitimated to fill the computational domain with prism elements. Since the design of single-mode, high-speed laser diodes has recently come to the focus of research, the determination of the laser mode intensities seemed an important issue under both static or dynamic conditions.

I wished to apply the future models on realistic advanced laser diodes. These contain noncylindrical oxide apertures, specially shaped surface reliefs or deep-etched photonic crystal VCSELs. It emerged as a natural choice to compare the simulation results with previous theoretical models, as well as with measured device characteristics.

Novel Results

1. I have developed two new semianalytical extensions of the weighted index method, and applied for the simulation of a multi-mode VCSEL incorporating an oxide aperture that exhibits a realistic contour between an ideal circle and the encased square. The calculated wavelength spacing among the fundamental and the next three modes has agreed convincingly with the recorded spectrum, and the measured near field patterns have also been reproduced by weighting the first few predicted transverse mode profiles [1, 2].

2. I have realized the direct numerical solution of the Helmholtz equation for noncylindrical VCSELs, and demonstrated the diffraction of the light near their oxide windows. Two model apertures have been simulated, one possessing a curved tetragonal shape, the other an ellipse with moderate eccentricity. Both cases have shown agreement with one's qualitative expectation that stronger scattered waves should appear along the shorter sections of the aperture [3, 4].

3. I have revealed significant cold-cavity modal loss difference with the fully numerical solution of the vector Helmholtz equation between the two orthogonally polarized fundamental modes of a VCSEL that possesses an elliptical oxide aperture. The structure, in which only the topmost quarter-wavelength thick layer was partially etched to form an elliptical surface relief, has yielded smaller loss difference; and an exciting intensity distribution at the top surface due to the detuning of the axial standing wave below the etched region [3, 5].

4. I have confirmed and explained the previous experimental finding that an oxide aperture could lead to reduced threshold current in PhC-VCSELs, by invoking the Helmholtz equation solver. It has been proved that the extra guiding introduced by the oxide squeezed the laser modes further towards the center axis, and decreased the scattering loss on the deep

etched holes. As stronger effect has been found for the higher modes, the dielectric aperture can deteriorate single-mode operation in PhC lasers [3, 6].

5. I have predicted the static light power versus injection current characteristics of various noncircular VCSELs using the coupled three-dimensional opto-electro-thermal approach, and assuming cold-cavity laser modes. In a laser diode possessing a square-like aperture shape, the degeneracy splitting between the second-order modes and the asymmetric current distribution have together resulted in noticeable peaks on the calculated near field pattern, which has matched to the experimental image. I have pointed out with numerical modeling that this behavior could be reversed, if quarter-wavelength deep triangular holes are etched into the top mirror above the corners of the aperture. A similar light power versus current diagram has also been estimated for a VCSEL with an elliptical surface relief but cylindrical structure elsewhere, and it has indicated the suppression of transverse modes that overlap substantially with the etched region [7-9].

6. I have optimized with simulation the lattice constant of a proton-implanted PhC-VCSEL to achieve the highest single-mode output power. To this end, the coupled opto-electro-thermal analysis has been utilized, and the laser modes have been consequently recalculated at different injection levels. It has been obtained that higher order modes became more easily unsupported by the PhC, and the modal discrimination strengthened as the lattice constant decreased. On the other hand, the threshold current has decreased and the maximal laser power has scaled naturally for larger optical mode area. These competing effects have made clear the existence of an optimal lattice constant that corresponds to the highest single-mode power, which has been verified experimentally, as well [10-14].

Utilization of the Results

The approaches that I have developed form the core of a software package created and extended continuously by the Furukawa Electric Institute of Technology. This tool is used for the design of VCSELs in Hungary and in Japan. The numerical optimization results exposed in the sixth thesis are closely related to the typical motivations of industrial development. I have also significantly contributed with calculations to three patents, one of which is referred in the dissertation.

Publications Related to the Dissertation

- [1] P. Nyakas, Zs. Puskás, T. Kárpáti, T. Veszprémi, Gy. Zsombok, G. Varga, and N. Hashizume, "Optical simulation of vertical-cavity surface-emitting lasers with non-cylindrical oxide confinement," *Opt. Commun.*, vol. 250, pp. 389–397, 2005.
- [2] P. Nyakas, G. Varga, T. Kárpáti, T. Veszprémi, Gy. Zsombok, Zs. Puskás, and N. Hashizume, "Optical simulation of vertical-cavity surface-emitting lasers with non-cylindrical oxide confinement," Conference on Lasers and Electro-Optics Europe, CLEO/Europe 2003, 2003, CC6W.
- [3] P. Nyakas, "Full-vectorial three-dimensional finite element optical simulation of vertical-cavity surface-emitting lasers," *J. Lightwave Technol.*, vol. 25, pp. 2427-2434, 2007.
- [4] P. Nyakas, G. Varga, T. Kárpáti, T. Veszprémi, Gy. Zsombok, Zs. Puskás, and N. Hashizume, "Real three-dimensional optical simulation of non-nircular VCSEL structures with finite volume method," Proceedings of the 4th International Conference on Numerical Simulation of Optoelectronic Devices, NUSOD '04, 2004, WP2.

- [5] P. Nyakas, "Three-dimensional VCSEL simulation using vector finite elements", Proceedings of the 5th International Conference on Numerical Simulation of Optoelectronic Devices, NUSOD '07, 2007, TuP11.
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- [7] P. Nyakas, G. Varga, Zs. Puskás, N. Hashizume, T. Kárpáti, T. Veszprémi, and Gy. Zsombok, "Self-consistent real three-dimensional simulation of vertical-cavity surface-emitting lasers," *J. Opt. Soc. Am. B*, vol. 23, pp. 1761–1769, 2006.
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- [9] P. Nyakas, Zs. Puskás, T. Kárpáti, T. Veszprémi, Gy. Zsombok, G. Varga, and N. Hashizume, "Real three-dimensional dynamical VCSEL simulation with spatially distributed noise sources," Proceedings of the 5th International Conference on Numerical Simulation of Optoelectronic Devices, NUSOD '05, 2005, TuC3.
- [10] T. Kise, N. Yokouchi, and P. Nyakas, "Surface Emitting Lasers" (translated), Patent application number: JPA2007-046823, Date of application: 2007/02/27.
- [11] T. Kise, P. Nyakas, K. Maruyama, K. Kiyota, and N. Yokouchi, "Thermal lens effect on single-transverse-mode stability of proton-implanted photonic-crystal vertical-cavity surface-emitting lasers", The 20th annual meeting of the IEEE Lasers and Electro-Optics Society, LEOS 2007, 2007, WZ5.

- [12] P. Nyakas, T. Kise, T. Kárpáti, and N. Yokouchi, "Numerical optimization of single-mode photonic crystal VCSELs", accepted to NUSOD '08, 2008.
- [13] T. Kise, K. Kiyota, K. Maruyama, N. Yokouchi, P. Nyakas, and N. Hashizume, "Transverse mode stability of proton-implanted photonic-crystal vertical cavity surface emitting lasers", The 54th Spring Meeting, the Japan Society of Applied Physics, 2007, 29a-SG-6.
- [14] T. Kise, P. Nyakas, K. Maruyama, K. Kiyota, and N. Yokouchi, "Single transverse mode analysis of proton-implanted photonic-crystal vertical-cavity surface-emitting lasers", The 68th Autumn Meeting, the Japan Society of Applied Physics, 2007, 8a-C-4.

Further Publications

- [15] T. Kise, N. Yokouchi, P. Nyakas, and Gy. Zsombok, "Surface Emitting Lasers" (translated), Patent application number: JPA2007-025240, Date of application: 2007/02/05.
- [16] T. Kageyama, N. Iwai, Y. Kawakita, K. Takaki, and P. Nyakas, "Surface Emitting Laser Element and Method of Fabricating the Same," Patent application number: US 12/057538, Date of application: 2008/03/28.