Calculating the Optical Modes of Realistic VCSEL Devices

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A key issue in the numerical simulation of VCSEL devices is an appropriate method to treat the optical resonator. In mathematical terms, the physics in the optical resonator is governed by a complex eigenproblem. The solution of this eigenproblem consists of the optical field pattern (eigenvector), the resonance frequency (real part of the eigenvalue) and the field decay constant (imaginary part of the eigenvalue). The optical field must be analyzed rigorously in order to calculate mode confinement, radiating waves and guided surface waves (Fig. 2). The decay constant includes Bragg losses as well as diffraction losses, which is very important for the determination of the laser threshold current.

In this work, VCSEL optical resonators with a realistic size and structure are investigated (Fig. 1). The device structure under investigation is grown on a GaAs substrate and AlAs/GaAlAs layered medium is applied to form Bragg mirrors [1]. In the device center, a λ-cavity forms the microcavity. An etched-mesa type optical confinement is assumed. However, it has to be emphasized that the method is applicable for a wide range of device structures because there are no device-specific fitting parameters and the approach is purely physics-based.

The eigenproblem is solved by a combination of the finite-difference time-domain (FDTD) method and the Padé approximation [2]. For the FDTD calculation, a Fourier series expansion is applied in the rotational direction. The cavity is illuminated by a pulse source in the center of the device. A large number of modes are excited by this source. However, the fundamental mode decays much slower than the high-order modes because of the frequency selective Bragg mirrors. Therefore, there is only a small number of modes present after a relatively short period of time. With the use of the Padé approximation, the remaining modes are separated and the frequency-domain data can be obtained from the time-domain analysis.

Alternatively, the finite-element method (FEM) can be used to calculate the optical modes of the VCSEL resonator, as proposed by [3]. The comparison of the two methods shows that FDTD has a clear advantage over FEM regarding computational resources: a realistic VCSEL structure with 130 dielectric layers and 6µm mesa width requires 240 MB of main memory and runs over-night on a Compaq AlphaServer (677MHz) workstation, if FDTD is employed. In contrast, using FEM to solve very large eigenproblems requires more memory and is only practicable with an iterative solver [4]. In order to achieve convergence, a good starting solution for the eigenpair is essential. This makes the combination of FEM and an iterative eigensolver suitable to calculate eigenpairs of a gradually perturbed problem based on an initial solution.

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[2] A. Witzig, M. Streiff, and W. Fichtner, “Time-domain Green’s functions of realistic VCSEL cavities”, *in Proc. of Photonics West, Physics and Simulation of Optoelectronic Devices IX*, San Jose, CA, January 2001.

[3] M. J. Noble, J. A. Lott, and J. P. Loehr, “Quasi-exact optical analysis of oxide-apertured microcavity VCSELs using vector finite elements”, *IEEE Journal of Quantum Electronics*, vol. 43, pp. 2327-2339, December 1998.

[4] D. Fokkema, G. Sleijpen, and H. van der Vorst, “Jacobi-davidson QR and QZ algorithms for the reduction of matrix pencils”, SIAM J. Sci. Comput., vol.20, no. 1, pp.94-125, August 1998.

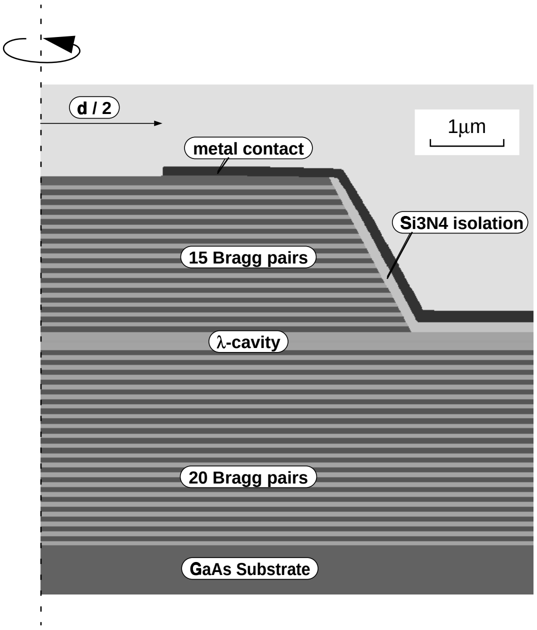

Fig. 1: Geometry of the VCSEL device. The Bragg mirror pairs consist of AlAs and GaAlAs with refractive indices of 3.02 and 3.47, respectively.

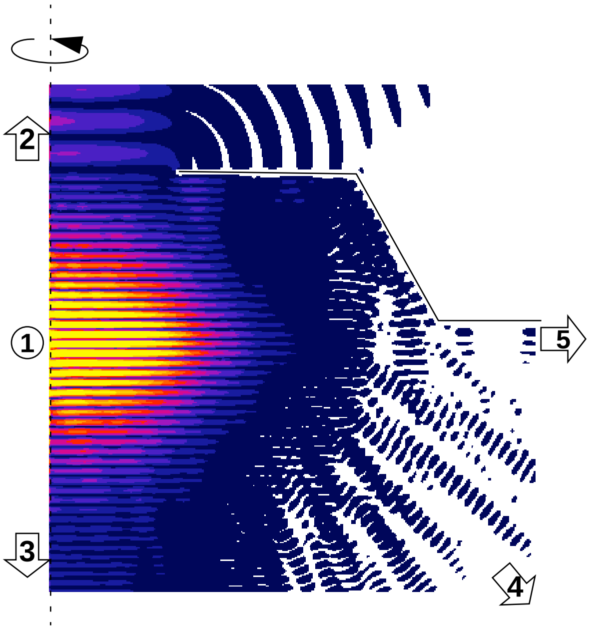

Fig. 2: Optical mode pattern of the fundamental mode. The real part of the complex eigenvector is shown in the figure. 1) Fundamental mode. 2) Laser output. 3) Bragg losses. 4) Radiating waves. 5) Guided surface waves.

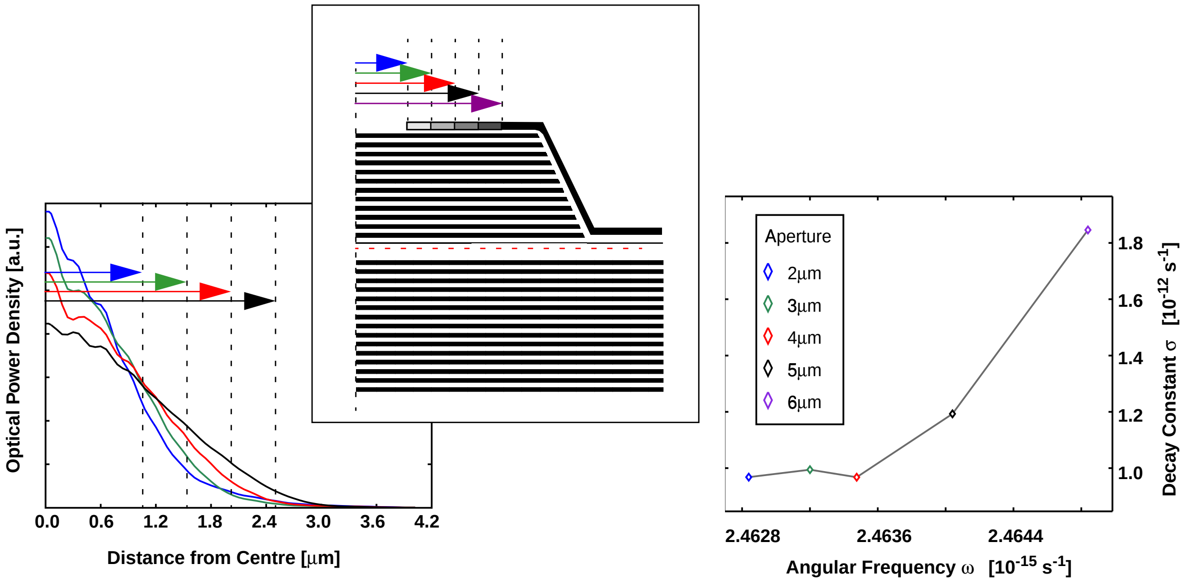

Fig. 3: Parameter variation. As a design parameter, the aperture of the VCSEL is varied as shown in the inset. Left: the optical field pattern in the active region. Right: the eigenvalue of the fundamental mode.