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Numerical Modeling of Vertical Cavity Semiconductor Lasers

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Numerical Modeling of Vertical Cavity Semiconductor Lasers

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Abstract

A vertical cavity surface emitting laser (VCSEL) is a diode laser whose optical cavity is formed by growing or depositing DBR mirror stacks that sandwich an active gain region. The resulting short cavity supports lasing into a single longitudinal mode normal to the wafer, making these devices ideal for a multitude of applications, ranging from high-speed communication to high-power sources (from 2D arrays). This report describes the development of a numerical VCSEL model, whose goal is to both further our understanding of these complex devices and provide a tool for accurate design and data analysis.

Introduction

A VCSEL circumvents the problems arising from edge emission by having its resonator axis in the vertical (epitaxial growth) direction. With the laser emission from the wafer surface, it is possible to have a symmetrical beam cross section, with low beam divergence. Surface emission also make possible the fabrication of two-dimensional laser arrays with high fill factors. Furthermore, the very short cavity length makes VCSEL inherently single mode. There are also advantages associated with growth and fabrication. The VCSEL mirrors are fabricated during the epitaxial growth using standard integrated circuit technology, so that hundreds of VCSEL structures, including the mirrors, can be grown simultaneously.

The vertical cavity geometry also result in technical issues that require attention. The significant reduction in the gain length places considerable demand on well designed optical resonator and gain structure. This report describes the development of a numerical VCSEL model, whose goal is to both further our understanding of these complex devices and provide a tool for accurate design and data analysis.

The investigation was carried out during FY 1992-1993 at Sandia as part of a Laboratory Directed Research and Development project.

Optical Model

A large fraction of this effort has been spent on the optical model because this important component proved to be more difficult than was initially expected. This added difficulty resulted from the high cavity Q that is characteristic of vertical cavity lasers, and the fact that the cavity mirrors are distributed reflectors. The former property disallows the use of iterative solution techniques because of the resulting slow convergence, while the latter property implies that a single reflection plane (such as is needed for beam propagation models) does not exist. After evaluating a number of unsuccessful candidates, we derived a new effective-index model that is stable, robust, and requires a minimum of computer resources. While approximate, this model has proven to be surprisingly accurate for most geometries. More importantly, however, its development has led to a new understanding of waveguiding in VCSELs that is revolutionary and suggests new designs for devices that are predicted to remain single mode throughout their current range. The validity of this effective index model has been checked by comparison with calculations made using a direct finite difference method. This comparison was very favorable for most device designs, even providing good

agreement for geometries that violate the assumptions employed in its derivation. We next include a brief derivation of the effective index method for VCSELs, and discuss the insights resulting from its use.

Lasing modes in a VCSEL are characterized by near-paraxial propagation normal to the mirror layers, with polarization in the plane of the mirrors. Under these conditions, only a single electric field component is appreciable, and we may describe that field with the scalar wave equation

$$\nabla^2 F - \frac{\epsilon}{c^2} \frac{\partial^2 F}{\partial t^2} = 0 \quad (1)$$

Since F depends on all three spatial coordinates and time, we cannot easily solve the above for a complicated structure such as a VCSEL. Instead, we invoke two simplifying assumptions: (1) that the time dependence is nearly harmonic with complex frequency ω_0 , and (2) that the device structure depends only upon z within each of a number of concentric cylindrical regions. Thus, we write for region i ,

$$F(r, z, \phi, t) \approx g(z)E(r, \phi, t)e^{-i\omega_0 t} \quad (2)$$

Substituting (2) into (1) results in

$$g_i'' E + g_i \nabla_{\perp}^2 E + \epsilon k_0^2 g_i E + 2i\epsilon k_0 g_i \frac{\partial E}{\partial \tau} = 0 \quad (3)$$

where we have introduced the vacuum wavevector $k_0 = \frac{\omega_0}{c}$ and the modified time coordinate $\tau = ct$, and have invoked the slowly-varying envelope approximation by neglecting second derivatives with respect to time when acting on the field amplitude E .

At this point, we introduce the effective index approximation by assuming that (1) the functions g_i each satisfy a 1D eigenvalue equation of the form

$$g_i'' + k_0^2(1 - \xi_i)\epsilon_i(z)g_i = 0 \quad (4)$$

where the complex eigenvalue ξ_i is related to the effective index, and (2) that the eigenfunctions g_i are all approximately identical in each of the problem regions. The latter statement embodies the essence of the effective index method by implying approximate separability, with the dominant effect of structure variations appearing primarily as a variation in the effective index. Consequently, we might expect the model to give inaccurate results when applied to devices with severe structural variations that violate

separability. Such effects are seen in simulations of oxide-confined VCSELs, with the mode size accurately predicted, but the scattering loss unaccounted for.

If we now use (4) to eliminate the g_i'' term in (3), we have

$$k_0^2 \xi \varepsilon_i(z) g E + g \nabla_{\perp}^2 E + 2ik_0 \varepsilon_i(z) g \frac{\partial E}{\partial \tau} = 0 \quad (5)$$

The z -dependence in (5) may be removed by multiplying by g^* and integrating over z , resulting in

$$k_0^2 \xi \langle \varepsilon_i \rangle E + \nabla_{\perp}^2 E + 2ik_0 \langle \varepsilon_i \rangle \frac{\partial E}{\partial \tau} = 0 \quad (6)$$

where we have defined

$$\langle \varepsilon_i \rangle \equiv \frac{\int g^* \varepsilon_i(z) g dz}{\int g^* g dz} \quad (7)$$

Equation (6) may be written in the form of a beam propagation equation where the propagation direction is the time-like variable $\tau = ct$. The result is

$$\frac{\partial E}{\partial \tau} = \frac{i}{2k_0 \langle \varepsilon_i \rangle} (\nabla_{\perp}^2 + k_0^2 \Delta \varepsilon_{eff}) E \quad (8)$$

where the variation in effective dielectric constant (effective index squared) is $\Delta \varepsilon_{eff} \equiv \xi_i \langle \varepsilon_i \rangle$.

Note that despite the familiar form of (8), it is in reality an expression of time variation, so that the model we are espousing is *not* a true beam propagation model. This distinction is clarified by the observation that in our model there is no necessity of defining an effective mirror penetration depth, as is the case with true beam propagation models. This is of considerable advantage for calculating the losses incurred, for example, by free carrier absorption resulting from mirrors grown using arbitrary doping profiles. The inclusion of such losses is awkward with a beam propagation approach, but appears naturally in our model as a contribution to the imaginary part of the eigenvalue ξ_i .

Considerable insight may be gained from the above derivation by examining in detail the expression for the effective dielectric constant:

$$\frac{\Delta \varepsilon_{eff}}{2 \langle \varepsilon \rangle} \approx \frac{\Delta n_{eff}}{n_{eff}} = \frac{\text{Re}(\xi)}{2} \quad (9)$$

But the eigenvalue ξ_i may be related directly to a variation in the 1D cavity resonance frequency that results from the assumed harmonic time dependence:

$$\frac{\text{Re}(\xi)}{2} = \frac{\Delta \omega}{\omega_0} = -\frac{\Delta \lambda}{\lambda_0} \quad (10)$$

Combining (9) and (10) we see that the variation in effective index at different positions in the VCSEL cavity is related simply to the Fabry-Perot resonance wavelength by

Fig. 1. Schematic of a hypothetical cavity with two cavity lengths. Radiation resonant in the left portion will tilt as it diffracts into the longer cavity in order to maintain the resonance condition.

$$\frac{\Delta n_{eff}}{n_{eff}} = \frac{\Delta \lambda}{\lambda_0} \quad (11)$$

This remarkable result implies that *variations in effective index within a VCSEL may be engineered by designing variations in cavity length, without the necessity of changing the material index*. An illustration of this principle is shown in Fig. 1. Radiation in the shorter cavity region to the left that is Fabry-Perot resonant and propagating normal to the mirror layers must change its propagation direction as it diffracts into the longer cavity region to the right in order to remain resonant. The angle of tilt shown in the figure is consistent with Eq. (11) for total internal reflection in a medium whose refractive index is as given by the equation. This effect may be realized in a device, for example, by

etching the GaAs cavity region within a VCSEL prior to growing the upper mirror stack, resulting in variations in effective index that will in turn influence waveguiding. In particular, positive changes in index may be easily brought about, allowing the design of antiguided (leaky-mode) devices. This category of lasers, which has been shown to result in single-mode operation in edge-emitting arrays, has heretofore been virtually impossible to achieve with VCSELs, due to the difficulty of regrowing high-index material and still maintaining upper mirror integrity. Our simulations indicate that leaky-mode VCSELs should have very desirable operation characteristics, and we have thus recently initiated an experimental effort to fabricate such devices based upon the relationship described in Equation (11).

The time-dependent Equation (8) has been incorporated into the self-consistent VCSEL model in addition to other equations that describe (1) the transport of carriers through the cladding layers, (2) the transport of heat from the active region towards the heat sink, and (3) the diffusion of electrons and holes within the quantum wells. Carriers within the quantum well are allowed to recombine both radiatively and non-radiatively. Radiative recombination results in gain of an amount described by our gain model detailed below. Since the gain is saturable and spatially varying, spatial hole-burning effects are accounted for automatically.

Gain Model

To model the active medium, we use semiclassical laser theory. In semiclassical laser theory, one treats the laser field classically, and the gain medium quantum mechanically. The lasing frequency and the strength of the optical transitions depend on the active medium bandstructure. We compute the bandstructure using a $\mathbf{k}\cdot\mathbf{p}$ theory, where modifications due to quantum confinement and strain are treated in the context of the envelope approximation. The electrons and holes in a semiconductor are charged particles, and therefore interact via the Coulomb potential. We refer to the interactions as many-body interactions because a laser typically has very high electron and hole densities. The effects of many-body Coulomb interactions include plasma screening, bandgap renormalization, Coulomb enhancement of optical transitions, thermalization of intraband populations, and polarization dephasing.

Optical gain models for determining the gain parameters used in the overall VCSEL code were assembled. These models are based on a quasi-equilibrium microscopic theory where bandstructure, band-filling and many-body Coulomb effects are consistently taken

into account. During the first year, gain models for GaAs-AlGaAs, InGaAs-AlGaAs and InGaAs-InP quantum well structures were developed. During the second year, the range was extended to include InGaP-AlGaInP and ZnCdSe-ZeSe quantum wells, and bulk GaN.

The VCSEL is characterized by a very short ($\cong \lambda$), high Q optical resonator that result in widely spaced, well defined resonances. There is typically only one longitudinal mode within the spectral gain region, which is desirable for many applications. However, this also lead to a laser threshold current is very sensitive to the alignment of this mode in relation to gain peak.

The position of the gain peak is influenced by band filling and many-body Coulomb effects. Band filling contributes to a blue shift of the gain peak, the extend of which depends on bandstructure. On the other hand, band gap renormalization shifts the gain peak towards longer wavelength. In addition, the gain peak frequency is affected by the reshaping of the gain spectrum by Coulomb enhancement. By carefully taking into account bandstructure and many-body Coulomb effects, our laser theory is able to provide accurate predictions of threshold current densities as functions of wavelength and temperature for a wide range of VCSEL structures. The results show the important role played by many-body Coulomb effects.

Conclusion

We developed a self-consistent VCSEL simulation code that is at present the most comprehensive in existence. This code has been benchmarked by comparing its predictions with experimental measurements for both index-guided and gain-guided VCSELs fabricated at Sandia. In addition to providing confidence in the accuracy of the code, these comparisons have produced added insights into current crowding effects and the importance of thermal lensing for implanted devices, and mode-dependent scattering losses for selectively-oxidized devices. Sandia's recent world-record successes with selectively-oxidized lasers have rendered these latter insights of particular importance, since our code now provides the only means of fully realizing the potential of these important structures. In addition, studies on the effects of strain and quantum confinement have led to the identification of critical design issues for short (visible) wavelength operation, and to a scheme for extending the temperature operating range of a VCSEL (TA SD5485).

The above self-consistent VCSEL code has been delivered to Optical Concepts, Inc. for inclusion of pre-and post-processors to enhance the utility of the code. In particular,

the porting of this code to produce a PC version, together with the construction of a "windows"-type user interface will render the code more useful to experimentalists for data analysis and device optimization.

Appendix, LDRD Summary

Refereed publications resulting for the work:

- G. Ronald Hadley, 'Effective index model for vertical-cavity surface-emitting lasers', Optics Letters, Vol. 20, 1483(1995).
- G. R. Hadley, K. L. Lear, M. E. Warren and K. D. Choquette, 'Comprehensive Numerical Modeling of Vertical-Cavity Surface-Emitting Lasers', accepted by the IEEE Journal of Quantum Electronics.
- W. W. Chow, R. P. Schneider, Jr., J. A. Lott and K. D. Choquette, 'Wavelength dependence of the threshold in an InGaP-InAlGaP vertical-cavity surface-emitting laser,' Appl. Phys. Lett. **65**, 135 (1994).
- S. W. Koch, F. Jahnke and W. W. Chow, 'Physics of semiconductor microcavity lasers,' **topical review**, Semiconductor Science and Technology **10**, 739 (1995).
- W. W. Chow, S. W. Corzine, D. B. Young and L. A. Coldren, 'Many-body effects in the temperature dependence of threshold in a vertical-cavity surface-emitting laser,' Appl. Phys. Lett. **66**, 2460 (1995).
- W. W. Chow and S. W. Koch, 'Many-body Coulomb effects in room-temperature II-VI quantum well semiconductor lasers,' Appl. Phys. Lett. **66**, 3004 (1995).
- W. W. Chow, K. D. Choquette and P. L. Gourley, 'Effects of quantum well subband structure on the temperature stability of vertical-cavity semiconductor lasers,' Appl. Phys. Lett. **66**, 3266 (1995).
- W. W. Chow, M. H. Crawford and R. Schneider, Jr., 'Minimization of threshold current in short-wavelength AlGaInP vertical-cavity surface-emitting lasers,' IEEE J. of Selected Topics in Quantum Electron. **1**, 649 (1995).
- W. W. Chow, R. Indik, A. Knorr, S. W. Koch and J. V. Moloney, 'Time-resolved non-degenerate four-wave mixing in a semiconductor amplifier,' accepted Phys. Rev. A.
- W. W. Chow, A. Knorr and S. W. Koch, 'Theory of laser gain in group III-nitrides,' accepted APL.
- W. W. Chow, K. D. Choquette and P. L. Gourley 'Improved temperature stability for vertical-cavity surface-emitting lasers,' (patent disclosure TA SD5485)

All other reports and publications from the work: 1

Number of patent disclosures: 1

Number of patent applications: 1

Number of patents: 0

Number of copyrights: 0

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