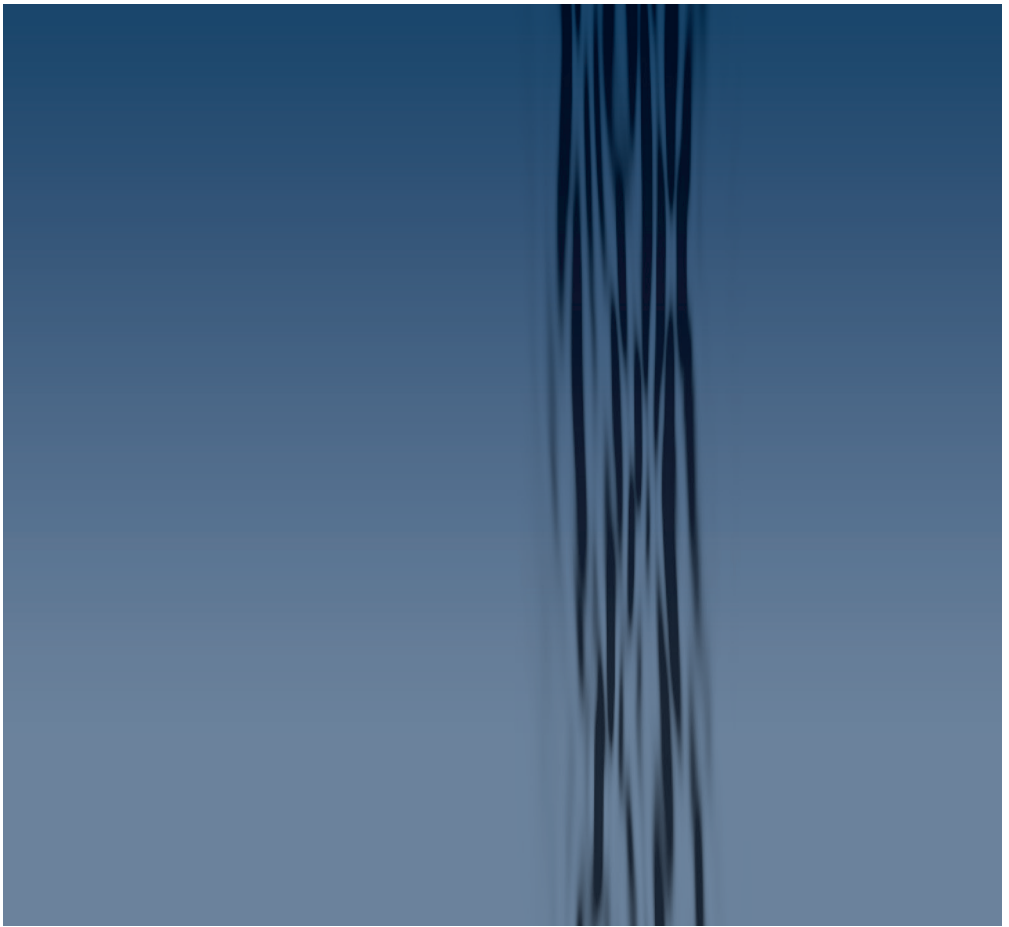




Modeling of the Lateral Emission Characteristics of High-Power Edge-Emitting Semiconductor Lasers

Carlo Holly

Modeling of the Lateral Emission Characteristics of High-Power Edge-Emitting Semiconductor Lasers

*Modellierung der lateralen Abstrahlcharakteristik von
Hochleistungsdiodelaser-Kantenemittern*

Von der Fakultät für Maschinenwesen der Rheinisch-Westfälischen Technischen
Hochschule Aachen zur Erlangung des akademischen Grades eines Doktors der
Naturwissenschaften genehmigte Dissertation

vorgelegt von

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Carlo Holly

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New York, April 2019

Carlo Holly

Abstract

In this work, numerical methods for the simulation of broad-area edge-emitting semiconductor lasers are presented. Frequency-domain and time-domain models are employed to predict the propagation of the filamented optical field in the semiconductor laser and determine emission characteristics including near-field and far-field profiles, beam width, divergence angle, and power over current. The models utilize wave-optical beam propagation and account for the interaction of the optical field with the spatial (and temporal) varying carrier and temperature distributions inside the semiconductor laser cavity. Once calibrated, the frequency-domain model is utilized to predict emission characteristics of single emitters and laser arrays, which differ in geometrical properties (contact width, cavity length or emitter pitch), epitaxial structure or facet reflectivity. By comparison with experimental data for eight laser designs, which include single-emitter and laser arrays it is demonstrated that the frequency-domain model allows computation of lateral far-field angles and near-field widths as a function of current and thermal state for edge-emitting diode lasers.

An opto-mechanical model is derived to compute the degree of polarization for packaged single emitter or laser arrays. The mechanical strains, induced by the soldering process, heating of the device during operation and intrinsic lattice mismatch in the device, are considered. The ratio of the shear strain and the lateral (and vertical) strain component(s) determines the degree of polarization.

In addition to the frequency-domain model, a time-domain model based on the traveling-wave method is implemented and employed to compute the optical propagation in the QW-plane of an edge-emitting diode laser, including carrier- and temperature-induced refractive index changes. The evolution of the optical field along the cavity is computed iteratively for transverse slices. Alongside with the optical propagation, the carrier diffusion equation and an auxiliary equation for the material polarization are solved. The results obtained with the time-domain model obey similar filamented field profiles like the ones obtained with the frequency-domain model.

In summary, the numerical model acts as a *digital-twin* of the real device and with the simulation tools presented in this work the lateral emission characteristics for edge-emitting laser devices can be predicted to the extent needed to make design decisions.

Zusammenfassung

Im Rahmen dieser Arbeit werden numerische Methoden zur Simulation von Breitstreifen-Kantenemitter Halbleiterlasern entwickelt und untersucht. Dazu werden Modelle in der Frequenz-Domäne und in der Zeit-Domäne herangezogen, um die Propagation des filamentierten optischen Feldes im Halbleiterlaser vorherzusagen und Abstrahlcharakteristiken, wie Nah- und Fernfeldprofile, Strahlbreite, Divergenzwinkel und Ausgangsleistung über Betriebsstrom zu bestimmen. Für die Modelle werden wellenoptische Propagationmethoden eingesetzt und die Kopplung des optischen Feldes mit dem räumlich (und zeitlich) variierenden Ladungsträger- und Temperatur-Verteilungen in der Kavität des Halbleiterlasers berechnet. Nach Kalibration werden, basierend auf dem Model in der Frequenz-Domäne, Abstrahlcharakteristiken von Einzelemittlern und von Emittern aus Laserbarren berechnet, die sich in geometrischen Eigenschaften (Injektionskontaktbreite, Kavitätslänge oder Emitterabstand), der epitaktischen Struktur oder der Facettenreflektivität unterscheiden. Durch Vergleich mit experimentellen Daten von acht unterschiedlichen Diodenlasern wird demonstriert, dass das Model in der Frequenz-Domäne die Vorhersage von lateralen Fernfeldwinkeln und Nahfeldbreiten in Abhängigkeit des Betriebsstroms und der Temperatur des Kantenemitters erlaubt.

Um den Polarisationsgrad von Einzelemittlern oder Laserbarren zu berechnen, wird ein opto-mechanisches Model entwickelt. Unter denen in Betracht gezogenen mechanischen Einflüssen sind Verspannungen durch den Lötprozess, Aufheizen des Lasers im Betrieb und durch unterschiedliche Gitterkonstanten im Halbleiter. Das Verhältnis von Scherspannung zu lateralen (und vertikalen) Spannungskomponenten bestimmt den Polarisationsgrad des emittierten Feldes.

Zusätzlich zum Model in der Frequenz-Domäne, wird basierend auf der *traveling-wave* Methode ein Zeit-Domänen Model implementiert und angewendet, um die räumliche und zeitliche Entwicklung des optischen Feldes in der Quantengraben-Ebene eines Halbleiterlaser-Kantenemitters zu berechnen. Dabei umfassen die Berechnungen die durch Ladungsträger und Temperatur induzierten Brechungsindexvariationen. Die Evolution des optischen Feldes entlang der Laserkavität erfolgt iterativ für transversale Querschnitte. Die Ergebnisse, die mit dem Model in der Zeit-Domäne berechnet werden, gleichen denen des Frequenz-Domänen Modells im Hinblick auf Filamentierung des optischen Feldes.

Zusammenfassend agiert das numerische Modell als *Digitaler-Zwilling* des realen optoelektronischen Bauteils. Mit den Simulationswerkzeugen, die im Rahmen dieser Arbeit vorgestellt werden, können die lateralen Abstrahlcharakteristiken von Hochleistungsdiodenlaser-Kantenemittern so präzise vorhergesagt werden, dass in Zukunft Entscheidungen für neue Designs aus der Simulation abgeleitet werden können.

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