Numerical Optimization of Single-Mode Photonic Crystal VCSELs

Péter Nyakas¹, Tomofumi Kise², Tamás Kárpati¹, and Noriyuki Yokouchi²

(1) Furukawa Electric Institute of Technology, Hungary
(2) Furukawa Electric Corporation, Japan

(NUSOD ’08, WB5)
Outline

Introduction
- Photonic crystal (PhC) VCSELs
- Single-mode condition defined by waveguiding
- Loss discrimination effect

3-D coupled simulation model
- Electro-thermal models
- Direct solution of Helmholtz equation
- Rate-equation approach

Results
- Current and temperature distributions
- Optical mode profiles and loss discrimination
- Static light power versus current (L-I) diagrams

Summary and outlook
Photonic Crystal VCSELs

- Optical confinement: PhC and optionally oxide aperture
- Electrical confinement: proton-implant or oxide aperture
- They potentially offer high-power single-mode operation.
- Design parameters: lattice constant (\(\Lambda, a\)), hole diameter (d) or diameter-to-pitch ratio, etching depth, and the diameter of the electrical aperture.
**Single-Mode PhC-VCSELs**

**Normalized frequency parameter**

\[
V_{\text{eff}} = \frac{2\pi r}{\lambda} \sqrt{n_{\text{eff}}^2 - (n_{\text{eff}} - \gamma \Delta n)^2}
\]  

- \(n_{\text{eff}}\): refractivity of core
- \(\Delta n\): index change introduced by full PhC
- \(\gamma\): etching depth factor (0–1)
- \(V_{\text{eff}} < 2.405\) corresponds to the single-mode regime [2]

**Normalized propagation constant**

- 2-D Helmholtz equation for the transverse cross section (fully etched VCSEL)
  \[
  B = \left( \beta_{\text{mode}}^2 - \beta_{\text{core}}^2 \right) / \left( \beta_{\text{clad}}^2 - \beta_{\text{core}}^2 \right)
  \]
  - \(\beta\): propagation constant
  - \(B_{LP01} < 0.57\) corresponds to the single-mode regime [3]

It was shown experimentally [4] and with simulations that not only the modes’ confinement but also their losses influence the single-mode condition. 

Plane wave admittance method [5] and finite element method [6] were applied, both for cold-cavity case.


Introduction
- Photonic crystal (PhC) VCSELs
- Single-mode condition defined by waveguiding
- Loss discrimination effect

**3-D coupled simulation model**
- Electro-thermal models
- Direct solution of Helmholtz equation
- Rate-equation approach

Results
- Current and temperature distributions
- Optical mode profiles and loss discrimination
- Static light power versus current (L-I) diagrams

Summary and outlook
**Electro-thermal equations** [7]

- Laplace equation for the electrostatic potential ($\Phi$)
- Anisotropic electric conductivity ($\sigma$) for heterojunctions
- Stationary solution of the heat conductivity equation with different heat sources ($R$)

$$\nabla (\sigma \nabla \Phi) = 0 \quad \quad c\rho \frac{\partial T}{\partial t} = \nabla (k \nabla T) + R_{nr} + R_{Joule} + R_{abs}$$

**Discretization**

- Definition of lateral regions by projecting all interfaces to the top plane
- Setting up prism elements that respect all interfaces
- Integration by finite volume method (box method)


(green: aperture, orange: implant, deep red: contact and PML, blue: holes)
Material Parameters

Temperature-dependent complex refractivity

- linear dependency of the real part of the index versus temperature
- its coefficient depends on the Al-composition of $\text{Al}_x\text{Ga}_{1-x}\text{As}$, and $\frac{1}{n'} \frac{dn'}{dT}$ varies between $1.25-4 \times 10^{-4} \text{ 1/K}$ [8]
- we used exponential temperature dependence for the imaginary part that corresponds to free-carrier absorption
- $T_0 = 180 \text{ K}$ was assumed irrespective of the composition due to the lack of more detailed experimental data [9]

Empirical gain function

$$g_i(n, T) = a_0 \ln \left( \frac{n}{n_0} \right) \left[ 1 - \left( \frac{\lambda_{\text{gain}}(T) - \lambda_i(T)}{\Delta \lambda} \right)^2 \right]$$

- the gain coefficient ($a_0$) and the transparency carrier density ($n_0$) can depend on temperature
- we assumed a parabolic effect of gain-to-cavity detuning

Scalar and vectorial solutions

- finite volume method was used to solve the scalar Helmholtz equation [7],
- and finite element method was applied to solve the vectorial Helmholtz equation [6]

\[
F(E) = \frac{1}{2} \int_V \left[ (\nabla \times E) \Lambda^{-1} (\nabla \times E) - \frac{\omega^2}{C_0^2} E \varepsilon E \right] dV
\]

- the scalar solution is used here because of its lower memory and runtime demands

Symmetry boundary conditions

- a 30-degree section is enough to calculate the scalar fundamental and some higher modes of a hexagonal PhC lattice
- a quarter cross-section is needed for LP_{11} and other higher modes

Cold-cavity and active cavity descriptions
- optical gain is \textit{not} included directly in the complex index when determining the laser resonator modes
- it is taken into account in the rate equation approach when following the evolution of the modes’ power
- however, local free-carrier absorption loss in the mirrors is included in the refractive index
- the real part of the index is updated according to the local temperature when calculating the mode profiles

Algebraic problem
- the complex-symmetric generalized eigenproblem is solved with preconditioned shift-invert iteration
- the convergence speed and the memory allocation can be tuned with the drop tolerance \cite{7}

\cite{7} P. Nyakas et al., JOSAB, 23, p. 1761 (2006)
Multi-Mode Rate Equations

- cover local radiative and nonradiative recombinations, lateral carrier diffusion and spatial hole burning
- the stationary solution is found using an ODE-solver after spatial discretization

\[
\frac{\partial n(r,t)}{\partial t} = \frac{\eta j(r,t)}{ed} - An - Bn^2 - Cn^3 + D\Delta n - \nu_g \sum_i g_i(n)|E_i|^2 S_i
\]

\[
\frac{dS_i(t)}{dt} = \beta B \int_{QW} n^2 dV + \nu_g \left[ \int_{QW} g_i(n)|E_i|^2 dV - L_i \right] S_i
\]
Coupled Simulations

Computer demands and simulation times

- it took about 2-3 GB memory and 20-60 minutes to find the fundamental mode once (30-degree section, 1.5m unknowns)
- it took about 10-25 GB memory and 10-30 hours to determine LP_{11} mode once (90-degree section, 4.2m unknowns)

Interpolation technique

- to accelerate the simulations for varying bias current,
- we estimated the temperature distribution at discrete points from the electro-thermal equations,
- and calculated the optical modes under these conditions
- the transverse mode profiles and the respective quantitative data were then interpolated for interior bias points
Introduction
- Photonic crystal (PhC) VCSELs
- Single-mode condition defined by waveguiding
- Loss discrimination effect

3-D coupled simulation model
- Electro-thermal models
- Direct solution of Helmholtz equation
- Rate-equation approach

Results
- Current and temperature distributions
- Optical mode profiles and loss discrimination
- Static light power versus current (L-I) diagrams

Summary and outlook
Target of Optimization

Fixed parameters
- design wavelength: 850 nm
- top-DBR: 30 pairs of p-doped Al$_{0.9}$Ga$_{0.1}$As/Al$_{0.2}$Ga$_{0.8}$As
- bottom-DBR: 35.5 pairs of n-doped Al$_{0.9}$Ga$_{0.1}$As/Al$_{0.2}$Ga$_{0.8}$As
- implant thickness: 12 pairs (about 1.5 μm)
- aperture diameter: 7.9 μm
- three rings of holes in a hexagonal pattern around a single defect
- hole diameter: 0.5 Λ
- we consider 2 modes

To be optimized
- lattice constant (3/4/5 μm) to obtain highest single-mode power in fundamental mode
The holes do not seem to impact drastically either the heat flow or the current flow. The electric conductivity may degrade also around the holes.
\( \Lambda = 4 \, \mu m, \, 0/10/20 \, mW \text{ heat dissipation} \)

\( \Lambda = 3 \, \mu m, \, 10 \, mW \text{ heat dissipation} \)

\( \Lambda = 5 \, \mu m, \, 10 \, mW \text{ heat dissipation} \)
- the transverse confinement increases with larger lattice constant and increasing bias current
- modal discrimination increases as the lattice constant shrinks
- it depends on the structure which of the two effects is dominant
- The threshold current increases, and the slope decreases for smaller $\Lambda$ due to higher optical loss and more wasted current.
- Single-mode operation can be maintained even if $\text{LP}_{11}$ gets confined, but suffers from high optical loss.
- Simulation and experiment agree in the optimal $\Lambda = 4 \, \mu\text{m}$.
Spatial Hole Burning
Results

- 3-D coupled simulation model for PhC-VCSELs
- The confinement and the modal loss discrimination effects have been compared
- Simulation and experiment have shown agreement in the optimal lattice constant that gives highest single-mode power

Further optimization

- Optimal ratio of the diameter of the optical and electrical confinements
- An oxide aperture provides lower differential resistance, but it can influence the mode confinement and also the losses
- Optimization of small-signal modulation response

Improve the electrical simulation

- Drift-diffusion model aiming realistic semiconductor behavior
- Check the dependence of the differential resistance on the holes’ diameters, and determine the effective hole size