3D Modeling of Superluminescent Light-Emitting Diodes
Outline

• Introduction
• Theoretical models based on Green’s function theory
• Results and comparison with experiments
• Summary
Introduction

- SLED is a light source with properties between those of LED and LD, high power, broad band and good directionality.
- Used in communication, sensing, and medical instruments.
- SLED spectrum is sensitive to carrier distribution inside MQWs.
- Accurate modeling tool is useful for the design.
Continue

- LED: spontaneous emission, broad band, low power
- LD: stimulated emission, narrow band, high power, high directionality
- SLED: amplified spontaneous emission, broad band, high power, high directionality
Theoretical Models

- So far, two types of model in literatures
  - 1-D wave equation along $z$ (propagation) direction. Neglects the carrier transport on transverse plane and lateral optical confinement.
  - 2-D carrier transport model, assumes uniform carrier distribution in $z$, and neglects spatial hole burning (SHB).

- Our approach combines 3-D carrier transport, 2-D transverse optical profile and 1-D optics along $z$
System of equations

3D drift-diffusion equation:

\[ \nabla \cdot \varepsilon \nabla \phi + q(n - p - N^+ D - N^A) = 0 \]

\[ \nabla \cdot J_n = U + q \frac{\partial n}{\partial t} \]

\[ -\nabla \cdot J_p = U + q \frac{\partial p}{\partial t} \]

Separating 3D optical field:

\[ E_\omega (x, y, z) = \sum_n E(z)_\omega \psi_n (x, y) \]

Transverse Helmholtz equation:

\[ \Delta_T \psi_n (x, y) + \frac{\omega^2}{c^2} \varepsilon \psi_n (x, y) = k_n^2 \psi_n (x, y) \]
Green’s function theory

1-D inhomogeneous Helmholtz equation

\[
\left[ \frac{\partial^2}{\partial z^2} + k_n^2(z) \right] E_\omega(z) = f_\omega(z)
\]

Green’s function is a solution of

\[
\left[ \frac{\partial^2}{\partial z^2} + k_n^2(z) \right] g(z, z_s) = \delta(z - z_s)
\]

Contribution of point source at \(z_s\) to the field at \(z\)
Solution

\[
E_\omega(z) = \int_0^L g(z, z_s)f_\omega(z_s)dz_s
\]

Spontaneous noise power

\[
\langle S_\omega(z) \rangle = \int_{-\infty}^{\infty} \langle E_\omega(z)E_\omega^*(z) \rangle d\omega'
\]

Z.Q. Li and Simon Li, IEEE JQE, vol.46, p.454, 2010
R. Loudon et al., J. Lightw. Tech., vol.23, 2491, 2005
Flow-chart

1. Initialize parameters
2. Increase bias
3. 2D optic: $\psi(x,y)$ Helmholtz FEM
4. 3D electric: $n, p, \phi$ drift-diffusion FEM
5. Green’s function: $E(z)$
6. Modal gain k.p method
7. Converged?
   - No
     - reduce bias
     - modal gain k.p method
   - Yes
     - Calculate power
Test device structure

QW1: 15nm
\(\text{In}_{53}\text{Ga}_{47}\text{As}\)

QW2: 6nm
\(\text{In}_{67}\text{Ga}_{33}\text{As}_{72}\text{P}_{28}\)

Barrier: 15nm
\(\text{In}_{86}\text{Ga}_{14}\text{As}_{30}\text{P}_{70}\)

Length: 300\(\mu\text{m}\)

Lateral mode profile

Multiple lateral modes can be included
Material gains of QW

QW1: two transitions
QW2: one transition
Broad band 1.3-1.6um

Band diagram at 0.7V
Carrier distribution at different injections

Carrier first captured in QW1, and in QW2 at high injection
Modal gain at different injections

![Graph showing modal gain at different injections for QW1 and QW2.]
Spatial hole burning is not negligible
I-V and L-I curves
Amplifier spontaneous emission
3D effect on ASE

Cavity length: 900 μm
3D effect shown at higher injections
Summary

- Comprehensive model for SLED simulation is presented. 3D carrier dynamics and longitudinal SHP are included.
- Carrier distribution is important for broad-band SLED.
- SHB is not negligible at high injections
- Full 3D simulation is necessary