# Acceleration of a Quasi-3D Spectral Laser Diode Simulator

J.J. Lim[1], S. Sujecki[1], P.J. Bream[1], N. Michel[2] and E.C. Larkins[1]
[1]The University of Nottingham, University Park, Nottingham, NG7 2RD, U.K. (e-mail: jun.lim@nottingham.ac.uk)
[2]Alcatel-Thales III-V Lab, RD128, 91767 Palaiseau, France.

*Abstract* – **In this work, we present a scheme to accelerate the convergence of a quasi-3D spectral laser diode simulator. It is demonstrated that the acceleration scheme allows the number of Fox-Li roundtrips to be substantially reduced. The accelerated spectral laser model is then used to simulate a narrow index guided 980nm tapered laser. The width of the simulated emission spectra is found to agree well with the measured spectra using an appropriate value of the spontaneous emission coupling factor.**

## I. INTRODUCTION

The emission spectra is important for many applications. For pump-lasers, the emission spectra has to be sufficiently narrow and stable to efficiently pump the amplifying medium, which has a narrow spectral absorption range. Engineering of spectra is also increasingly important for devices such as super-luminescent light-emitting diodes where a broad emission spectrum is desired [1].

Models for amplified spontaneous emission in the past have been largely focused on rate equations, which neglect propagation in the longitudinal direction. However, in devices such as tapered lasers, the longitudinal direction cannot be ignored. We have previously presented a quasi-3D spectral laser diode model which was used to explore the effect of carrier heating in a tapered laser. The initial model was found to be computationally demanding and required many round trips to reach convergence. In this work, we look at a scheme to accelerate the convergence of the quasi-3D spectral laser diode model.

## II. SPECTRAL LASER MODEL

The continuous wave (CW) quasi-3D spectral laser diode model has been described in a previous publication [2] but the implementation of the spontaneous emission coupling was not described in detail. The spontaneous emission is commonly included as a source term in the Helmholtz wave equation

$$\nabla^2 E + k_0^2 (n^2 - n_{eff}^2) E = \beta_{sp} R_{sp}(\lambda) , \qquad (1)$$

where $\beta_{sp}$ is the spontaneous emission coupling factor and $R_{sp}$ is the spatially dependent spontaneous emission spectra.

We have taken the approach of including the spontaneous emission term by introducing a perturbation to the complex refractive index distribution according to the following equation

$$\Delta n_{rsp} = i\sqrt{\frac{\beta_{sp} R_{sp}(x,\lambda)}{k_0^2 |E|}} . \qquad (2)$$

The perturbation given by Eq. (2) can be derived by rearranging Eq. (1) to arrive at the Helmholtz equation without the source term. This perturbation to the refractive index was found to be a convenient way of coupling the spontaneous emission into the wave equation and is straightforward to implement in any finite difference beam propagation (FD-BPM) scheme. The above scheme also ensures that amplification of the spontaneous emission takes place during the propagation of the optical fields.

## II. ACCELERATION SCHEME

The acceleration scheme employed in this work is based upon the idea of extrapolating the initial fields to accelerate the convergence of the output power spectra. Initially, the simulation is allowed to run normally until the carrier distribution has settled down to a quasi-steady-state (the spectral partitioning of the optical power has not settled down). Then, the carrier density distribution is kept fixed and the extrapolation of the power spectrum at the back facet is performed according to the procedure which is described next. To extrapolate the fields forward in iteration number, we require a knowledge of the round-trip gain. If we assume that the fields increase after each round trip according to Eq. (3)

$$P_k(\lambda) = P_{k-1}(\lambda) \exp(g_{rt}(\lambda) 2L) , \qquad (3)$$

where $P$ is the power at the back facet and $k$ is the Fox-Li iteration number, then the round-trip gain $g_{rt}$ can be calculated given the knowledge of the power at the back facet before and after one roundtrip of propagation. Using the extracted $g_{rt}$, the field at the back facet for the next iteration is extrapolated according to Eq. (4) using an acceleration factor $\delta$.

$$P_{k+1}(\lambda) = P_k(\lambda) \exp\left[\delta \cdot g_{rt}(\lambda) 2L\right] \qquad (4)$$

The extrapolation is performed separately for each wavelength $\lambda$.

To illustrate the acceleration scheme, a narrow index-guided tapered laser emitting at 980nm [3] is simulated using the quasi-3D spectral laser diode model. The gain was calculated using a parabolic band model for the conduction band and a 4x4 **k.p** band mixing model for the valence band. The change in the real index spectra was obtained using the Kramers-Kronig transformation of the gain difference spectra. The procedure employed to calibrate the non-radiative recombination parameters are as described in [4].

An example of the extrapolation scheme on the spectral simulation of a tapered laser is shown in Fig. 1. In Fig. 1, the extrapolation is performed after every 20 normal iterations (i.e. with the carrier density distribution solved self-consistently). The field is initially propagated one round trip using BPM and a value for $g_{rt}$ is calculated. The power at the back facet is then extrapolated using Eq. (4) with $\delta$=5. Using the new extrapolated power at the back facet, the field is propagated one round trip again through the cavity and a new value for $g_{rt}$ is calculated. The process is repeated for subsequent round trips. The extrapolation process is illustrated more clearly in the flow-diagram in Fig. 2. The extrapolation is performed for five times and then the simulation switches back to 20 normal iterations. It was found necessary to revert back to the normal iteration since the carriers have not converged during the start of the extrapolation procedure. It is also highlighted that since the electro-thermal solvers are not used during the extrapolation procedure, the simulation time is also reduced during the extrapolation process. This process of alternating between normal and extrapolation iterations is repeated until convergence is obtained. As seen in Fig. 1, with extrapolation turned on, the convergence of the modes is faster, whereas without extrapolation (Fig. 3), the modes still require a large number of round trips to converge. The marker at 966.1nm shows that the accelerated scheme has converged after 500 roundtrips at that particular wavelength (Fig. 1), whereas without the acceleration scheme, the mode is still decreasing in power as a function of roundtrip (Fig. 3). It should be noted that the acceleration depends on the choice of the parameter $\delta$, the wavelength spacing and the spontaneous coupling coefficient $\beta_{sp}$. In the example presented here, with a small wavelength spacing and small coupling coefficient, the simulation requires a significant number of roundtrips before convergence even with the extrapolation scheme. By optimising the acceleration parameter $\delta$, it is expected that the convergence could be accelerated further.

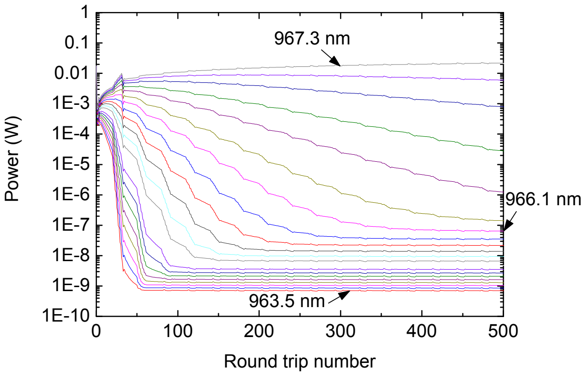

Fig. 1. Evolution of power distribution with round trip number *with* the acceleration scheme at a bias voltage of 1.50V. Only modes lower than the peak wavelength are shown with a spacing of 0.2 nm for clarity.

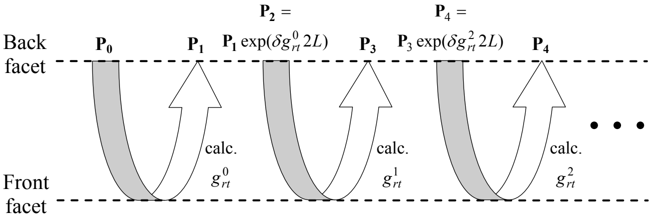

Fig. 2. Flow diagram demonstrating the extrapolation procedure.

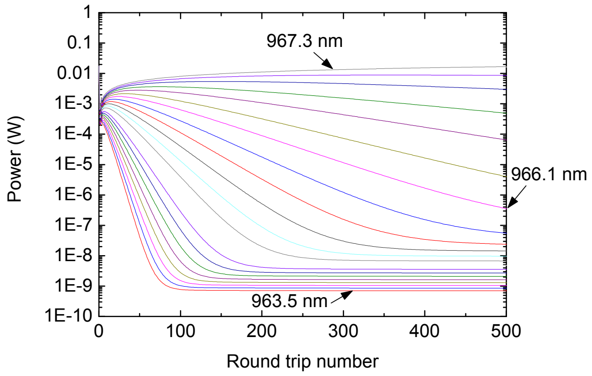

Fig. 3. Evolution of power distribution with round trip number *without* the acceleration scheme. The remaining conditions are as in Fig. 1.

The converged spectra is shown in Fig. 4 for bias voltages of 1.50 and 1.60V. A red-shift in the emission spectra is seen when the bias is increased, which can be attributed to self-heating and spatial hole burning effects. The shift of the peak wavelength is consistent with experimental observations. The emission linewidth was found to be controlled by the spontaneous emission coupling factor $\beta_{sp}$. With $\beta_{sp}$ = 1x10$^{-18}$, the emission linewidth (~0.5nm FWHM) was found to agree with experiment (~0.4nm FWHM). Good agreement is observed between the simulated and measured [3] power-current (L-I) characteristic as shown in Fig. 5. The roll-over in the measured L-I characteristic is due to the presence of larger self-heating in the experimental device at high bias. The thermal impedance of the heat sink could be adjusted in the simulation to obtain better agreement with the experimental characteristic at high bias.

## ACKNOWLEDGEMENT

The authors gratefully acknowledge the EC-IST project WWW.BRIGHTER.EU (IST-035266).

## REFERENCES

[1] M. Loeser and B. Witzigmann, “Multidimensional electro-opto-thermal modeling of broad-band optical devices,” *IEEE J. Quantum Electron.*, Vol. 44, No. 5-6, pp. 505-514, 2008.

[2] P. J. Bream, J. J. Lim, S. Bull, A. V. Andrianov, S. Sujecki and E. C. Larkins, “The impact of nonequilibrium gain in a spectral laser diode model,” *Optical and Quantum Electronics*, vol. 38, pp. 1019-1027, Sep 2006.

[3] M.M. Krakowski, S. Auzanneau, M. Calligaro, O. Parillaud, P. Collot, M. Lecomte, B. Boulant and T. Fillardet, “High power and high brightness laser diode structures at 980 nm using Al-free materials,” *Proc. SPIE*, vol. 4651, pp. 80–91, 2002.

[4] J.J. Lim, S. Sujecki, L. Lang, Z. Zhang, D. Paboeuf, G. Pauliat, G. Lucas-Leclin, P. Georges, R. MacKenzie, P. Bream, S. Bull, K.-H. Hasler, B. Sumpf, H. Wenzel, G. Erbert, B. Thestrup, P.M. Petersen, N. Michel, M. Krakowski and E.C. Larkins, “Design and Simulation of Next-Generation High-Power, High-Brightness Laser Diodes,” *IEEE J. Select. Topics Quantum Electron.*, Vol. 15, No. 3, May/June 2009.

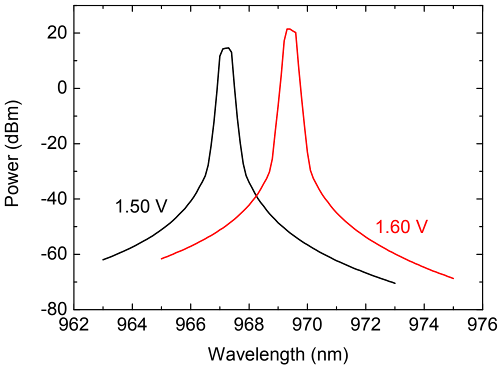

Fig. 4. Simulated emission spectra of tapered laser at bias voltages of 1.50 and 1.60V. The wavelength spacing used is 0.1nm.

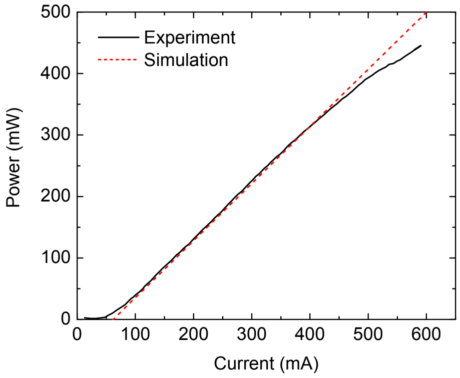

Fig. 5. Simulated and measured power-current characteristic. Experimental data taken from [3].