# NUMERICAL SIMULATION FOR InP/InGaAsP LASER DIODES

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#### Abstract

Numerical simulators for InP/InGaAsP laser diodes developed at NTT Opto-electronics Laboratories are reviewed. The programs are classified into two categories. One is overall simulation programs for designing optimum device structures such as low threshold designing by suppressing leakage current and reduced spatial hole burning designing. Carrier transport equations together with optical wave equation are solved self-consistently. Since the programs classified in this category are used repeatedly, user-friendly graphic interfaces are prepared during input and output stages. The other is an active layer design program based upon accurate physics such as strain and/or quantum well bandstructures. In this article, these simulators are introduced together with the more interesting results.

### I. INTRODUCTION

For optical device modeling, we have learned much from the experience of electron device modeling. The motivations for electron device modeling are: (1) Rapid progress in fabrication technology achieves very small devices including quantum effects. Therefore, conventional simple approaches based upon analytical expressions are no longer adequate. (2) The old fashioned design approach, *i.e.*, design, fabrication and measurement, requires a long turnaround time. (3) Simultaneously, the marked progress in LSI technology has changed computer hardware, *i.e.*, high-performance CPUs and memories. It has also brought numerical method progress. (4) Furthermore, we can well understand device physics through unmeasured parameters such as potential, carrier distribution and bandstructures of material. Although optical device structures are simple compared with electron devices, the motivations have made a similar impact on the development of optical device simulators, especially those for semiconductor laser diodes (LDs).[1]-[5]

This report describes the current status of semiconductor device modeling for InP/InGaAsP LDs at NTT Opto-electronic Laboratories. In our research group, attention is mainly focused upon application to the 1.55  $\mu$ m optical communication system. In Section II, an outline of a two-dimensional program is briefly introduced. This program is applied to understand current blocking mechanisms for buried heterostructure (BH) LDs for designing low threshold devices. In Section III, two- and three-dimensional simulations for distributed feedback (DFB) LDs including multielectrode structures are shown for a study of static wavelength shift. Strained layer quantum well LD modeling is described in Section IV.

## II. LEAKAGE CURRENT SUPPRESSION

A two-dimensional (xy plane: perpendicular to cavity) numerical simulator for Fabry-Perot LDs has been developed for designing leakage suppressed devices. The basic electrical equations, *i.e.*, Poisson's and current continuity equations for electrons and holes under Fermi statistics are solved self-consistently. The scalar wave equation is solved separately. Through recombination terms, the interaction between electrical and optical equations is described. Final self-consistent solutions can be obtained so as to balance the gain with loss. Here, problems are attributed to the large size of sparse matrix (Modified Incomplete Choresky Conjugate Gradient method[6]), and the high eigen value (zoomed Lanczos method[7]). A detailed algorithm is described in [8]. In the present program, the pre-processor covers the simulation input stage and the post-processor gives us a graphic display of the results.[9] An example of generated meshes is shown in the next section.

The two-dimensional program has been applied to BH LDs to study current blocking mechanisms. In order to achieve optical integration, such as in the LD array, the research subject for low threshold is very important. Figure 1 is a schematic of the device structure used here. Current blocking efficiency is usually determined by junction potential in the device. Current distribution has been calculated for two extreme cases, (a) including stimulated emission recombination (SER) above the lasing threshold and (b) excluding the SER. The lasing threshold is about 20 mA (1.05 V). Figure 2 shows current distribution at 1.25 V. It can be seen from the figure

that current injection efficiency for (b) is much degraded. Note that there are no serious differences between the two cases at slightly higher bias conditions from the threshold, 1.10 V.

Potential distribution in the devices is very helpful in understanding the difference between (a) and (b). Figure 3 shows junction voltage at the three heterointerfaces depicted in Fig. 1. In the vicinity of the threshold, the carrier is well confined even the three interfaces being biased forward. In Fig. 3(a), all the junction voltages are lower than the turn-on voltages of n-InP/p-InP homojunctions (dotted line in the figure) throughout the bias range shown here. Due to stimulated emission, the carrier density in the active region is kept nearly constant. This is the so-called potential pining effect. On the other hand, all of three junctions exceed turn-on voltage at 1.25 V for (b). Under these conditions, the current blocking effect is no longer expected. The figure shows that J2 plays a very important role in suppressing current leakage. It is clear from these results that excellent current blocking in BH LDs is achieved when all junction voltages in the blocking region are kept lower than the turn-on voltage in the constituent junction. In the actual device design, the leakage suppression is achieved by choosing the appropriate blocking layer impurity type, impurity concentration, and thickness.

### **III. STATIC WAVELENGTH SHIFT FOR DFB LDs**

The previous simulation program has been extended to three-dimensional spaces for DFB LDs' analysis--full three-dimensional calculations for electrical equations, and quasi-three dimensional treatment for optical equation, *i.e.*, coupled-mode equation[10] being solved for cavity (z) direction. The program has been applied to a single electrode DFB LD with  $\lambda/4$  phase shift ensuring a single mode lasing. Figure 4 shows the calculated optical intensity and electron concentration distribution under a lasing condition at the xz plane in the middle of an active layer. As seen in the figure, optical intensity near the phase shift is strong. Stimulated emission is proportional to the optical intensity and the carrier concentration near the phase shift is proportionally decreased. This is the so-called spatial hole burning effect, and it can be well understood from the figure. Using the program, we have studied static wavelength shift.[11] Similar studies for multielectrode DFB LDs are introduced below.

Multielectrode LDs give much flexibility in device designing, because nonuniform carrier distribution along the cavity can be controlled by changing injected current density. It has been reported that suppression of spatial hole burning results in improved FM response,[12] reduced linewidth,[13] and improved tunability.[14] Therefore, a two-dimensional program (yz plane)[15] has been developed based upon the experience with the three-dimensional program. By reducing one dimension, many more mesh points are placed in the z-direction to maintain accuracy without sacrificing CPU time. Figure 5 shows a schematic cross section of the three-section  $\lambda/4$  DFB LD used in the calculation. In the pre-process stage, suitable mesh points are generated interactively owing to a graphic friendly interface. The results are shown in Fig. 6.

Figure 7 shows the hole concentrations in two bias conditions. In the condition shown in Fig. 7(a), current is injected uniformly from the top electrode. It can be seen from the figure that the hole density distribution at the center of the cavity is decreased. The situation coincides with the right illustration in Fig. 4. Beyond this bias point, additional current is injected from the center electrode. This works to compensate the nonuniform carrier distribution as shown in Fig. 7(b). Through the present calculation, it is found that the cavity loss decreases with an increase in central current injection. Calculations have been made for different multielectrode dimensions. Figure 8 shows static wavelength shift due to refractive index distribution arising from the carrier nonuniformity shown in Fig. 7. These examples demonstrate that the current simulation program is effective in designing optimum device structures and optimum operation conditions.

### IV. STRAINED QUANTUM WELL LD DESIGN

Optimum designing of active layers is very important in achieving high-performance LDs. In quantum well (QW) LDs, it has been reported that biaxial compressive strain improves device performance such as in gain and differential gain characteristics. This improvement is caused by artificially controlling energy bandstructure by induced strain and quantum effects.[16,17]

We have recently reported the possibility of chirpless DFB LDs controlling strained QW structures, modulation doping and detuning.[18] Figure 9 shows the design concept. It shows the wavelength dependence of material gain and the linewidth enhancement factor ( $\alpha$  parameter) of a non-strained QW structure. Note that it is possible for DFB LDs to reduce the  $\alpha$  parameter by detuning shorter wavelengths. The important point is that the low  $\alpha$  value must be achieved not in

the absorption region but in the gain region. In order to control the gain curve, there are two superposable methods, (1) suitable design for QW structure--induced strain and well width, and (2) modulation doping.

For this purpose, exact gain and differential gain curves based upon accurate bandstructures are necessary. Fortunately, bandstructure information close to  $\Gamma$ -point plays an important role mainly from an LD application viewpoint. Especially, valence band structure can not be described by simple parabolic approximation, but it shows very complicated shape due to band mixing effects. Therefore, valence band structures have been calculated using 4X4 Luttinger-Kohn Hamiltonians including coupling between heavy and light hole subbands. Figure 10 shows the calculated density of state for valence band using the just mentioned bandstructure. It can be seen from the figure that the density of state is significantly reduced with an increase in strain. Figure 11 shows gain characteristics versus linewidth enhancement factor curves for different carrier densities. It is clear from the figure that the material gain is dramatically improved by induced low strain and modulation doping. Therefore, it is possible to achieve very low values of  $\alpha$  under low carrier injection conditions. Thus, the current program is useful in designing strained (not only compressive but also tensile strain) QW structures.

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Figure 1. Schematic of BH LD structure. The emission wavelength is 1.55 µm. The assumed reflectivity of both facets is 0.31.



Figure 2. Current flow distribution at 1.25 V for (a) with SER (stimulated emission recombination) and (b) without SER.



Figure 3. Junction voltage characteristics monitored at the junctions indicated in Fig. 1. (a) with SER, (b) without SER.



Figure 4. Calculated optical intensity and electron concentration distributions,  $I_{th} = 18.2 \text{ mA}, I = 3.5 \text{XI}_{th}$ , and P = 7.5 mW.



Figure 5. Schematic device structure for three-sectioned DFB LD with  $\lambda/4$  shift. Total cavity length  $(L_{s1}+L_{sp}+L_c+L_{sp}+L_{s2})$  of 300 µm,  $\kappa L = 2.0$ .





Figure 6. Example of generated meshes as pre-process stage on engineering workstation.



Figure 8. Calculated static wavelength shift caused by non-unifom carrier distribution in different electrode length ratios. Ratios in the figure indicate  $L_{s1} = L_{s2} : L_c$ .

Figure 7. Hole concentration distribution under (a) uniform carrier injection and (b) excess carrier injection at center electrode.



Figure 9. Wavelength dependence of material gain (solid line) and the linewidth enhancement factor (open circles) in non-strained QW with 90 Å well width.



Figure 10. Calculated density of state of valence band. Energy is measured from bulk valence band edge. The induced compressive strain values are 0, 0.5%, 1.0%, and 1.5%; corresponding well widths are 90 Å, 50 Å, 35 Å, and 27 Å.



Figure 11. Material gain versus linewidth enhancement factor using wavelength as a parameter for various carrier densities. (a) no strain, no doping, (b) 0.5% compressive strain with 2X10<sup>12</sup> cm<sup>-2</sup> background hole density caused by modulation doping.