# Simulation and Analysis of Single Mode Semiconductor Laser

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## Abstract

In this project, a Single Mode Semiconductor Laser Diode Model developed by [1] is studied and analyzed. Most of the experiment results from [1] are reproduced, and new simulations are conducted to observe the behavior of the Laser Diode within linear region. This Matlab based Model is proved to be very useful in the analysis of Laser Diode behavior within spontaneous photo emission and linear stimulation of photo phases, and also in the study of linearity compensation methods.

## Introduction

One of the most spectacular trends in today's telecommunications is the astonishing increasing of data transmission speed. This is due to the ever-increasing demand of users to communicate more graphical, more complex and more real-time information through networks. However, the bandwidth limits and simultaneous transmission modes limit are rather hard to overrule by traditional transmission ways, such as phone lines and cable. For this object, Fiber Optic System is coming to the rescue.

In Fiber Optic Systems, lighting source is a very important component in that it's characteristics gives an intense impact on the structure and performance of the whole systems. For optical fiber systems the laser sources used almost exclusively are semiconductor laser diodes. [2] As a lighting source, Laser Diodes need to meet it's threshold conditions in order to work linearly, so that electrical signal that stimulates the Laser Diode to emit correspondent optical signal to be transmitted through a fiber.

However, before and after the linear region that a Laser Diode works in, it responses nonlinearly to the input signal. Therefore, we need to analyze the specific working condition of a certain kind of Laser Diode to find a way to make its behavior meets our expectations. In this project, the Matlab Simulink based Single Mode Semiconductor Laser Diode Model works up to this goal.

## Theory

When analyzing a Laser Diode in an Optical Fiber Systems context, the first thing that comes to our concern is the relationship between optical output power and the diode drive current. And this has been dictated by rate equations. Due to the variety in the category of laser diode and mathematical models, one could find many different forms of laser diode rate equations through out the literature. In this project, the research group of [1] uses the rate equations applied by Javro and Kang [3]. It is written as below:

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$$\frac{dN(t)}{dt} = \frac{I(t)}{q \cdot V_a} - g_o \frac{[N(t) - N_o] \cdot S(t)}{1 + \varepsilon \cdot S(t)} - \frac{N(t)}{\tau_n} \qquad (1)$$

$$\frac{dS(t)}{dt} = \Gamma \cdot g_o \frac{[N(t) - N_o] \cdot S(t)}{1 + \varepsilon \cdot S(t)} - \frac{S(t)}{\tau_p} + \frac{\Gamma \cdot \beta}{\tau_n} \cdot N(t) \qquad (2)$$

$$\frac{d\phi(t)}{dt} = \frac{1}{2} \alpha \left[ \Gamma \cdot g_0 [N(t) - N_0] - \frac{1}{\tau_{\bar{p}}} \right] \qquad (3)$$

Equation (1) is for carrier density and equation (2) for photon density. And the last equation for optical phase.

This Laser Diode Model only simulates the first two operation regions of a Laser Diode, which are spontaneous emission of photons region and linear stimulated emission region as shown in figure 1 [1].

## Two Models

In this project, two models are designed to analyze the behaviors of Laser Diode in the first two phases.

Fig. 2 shows the Simulink based Large-Signal Model that simulates the behavior of Laser Diode from non-linear
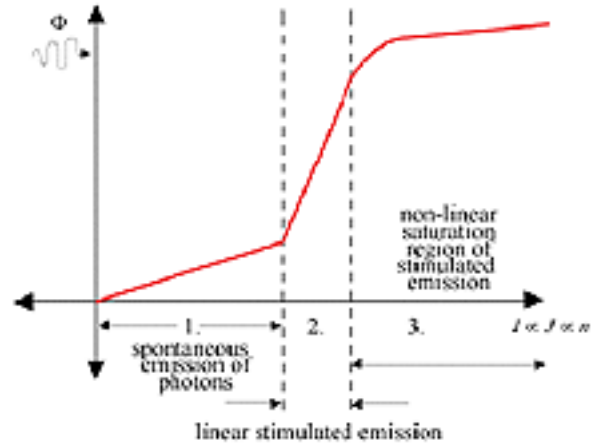


Figure 1. Full operating region of laser

region to linear region. The model is built according to the rate equations (1) and (2) as mentioned before.

The input signal is applied to the first input of the sum on the top left corner. It sums up with the pumping current to form the electrical impulse of the Laser Diode.
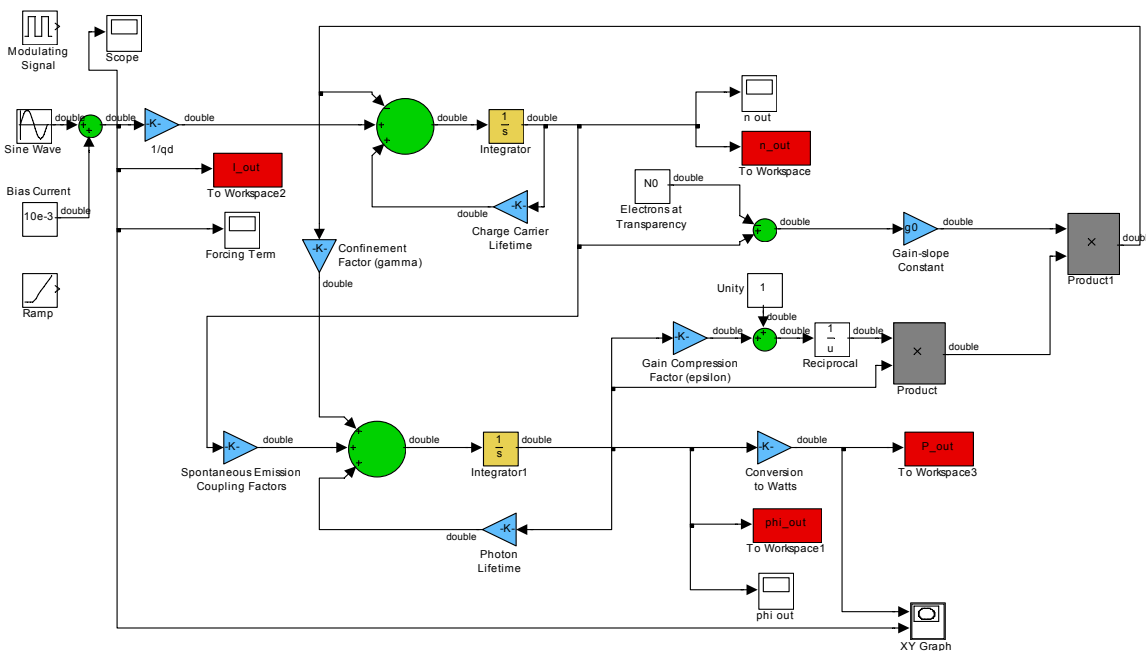
The components connected with the



Figure 1: Large-Signal Simulink Model

bigger sum in the upper part simulate the rate equation for carrier density. So we could capture the output of the carrier density from the end of this block.

Photon Density output comes from the output of the lower block connected with the lower bigger sum. It is also been converted to power output in watts.

Two scopes are branched out from those two outputs to observe the response of the system.

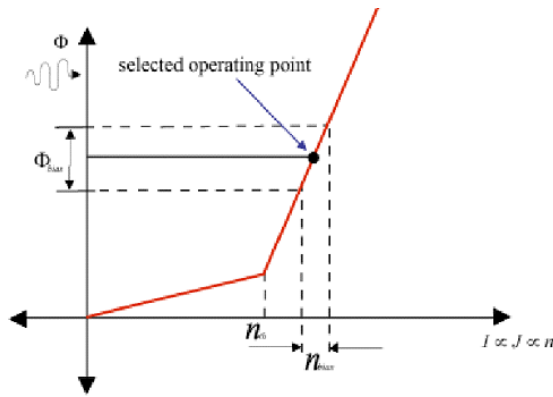When applying a ramp to the input of this Large-Signal Model, we could get



Figure 3 Selecting of Operating point.

the threshold point by observing the optical power output. Obviously when a big jump occurs in the output, and thereafter the output power changes linearly according to the input current, the threshold point (9mA for this model) is met.

Knowing the threshold current, we could arbitrarily choose two operating points (10mA and 15mA for this experiment) above the threshold points as illustrated in Fig 3. To find out the carrier density and photon density of the operating point, we need to simulate the model and record the two density outputs. These two values are useful for further use in completing the State Space Model that used in simulating the linearly working region.

The State Space Model (Equation (4) and (5)) is derived by linearizing the

$$\begin{bmatrix} \partial N/\partial t \\ \partial S/\partial t \end{bmatrix} = \begin{bmatrix} -\dfrac{1}{\tau_n} - g_o S & -g_o[N-N_o] \\ \Gamma g_o S + \Gamma\beta/\tau_n & \Gamma g_o[N-N_o] - \dfrac{1}{\tau_p} \end{bmatrix} \begin{bmatrix} N \\ S \end{bmatrix} + \begin{bmatrix} \dfrac{1}{qV} \\ 0 \end{bmatrix} I(t) \quad (4)$$

$$y = \begin{bmatrix} 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} N \\ S \end{bmatrix} \quad (5)$$

large-signal model, choosing operating point close to threshold point to let the gain saturation term $1/(1+\varepsilon S(t))$ approach 1 so that the impact of.$\varepsilon$ could be negligible.

By substituting N and S in (4) with the two density values achieved by simulating on operating points, we could get a complete State Space Model based on certain pumping current.

Then the simulation within linear region could begin.

## Simulation and Analysis

First of all, a rectangular pulse with frequency of 200MHz, amplitude of 0.25mA is applied to the input. Its delay is set to be 25ns. We use both 10mA and 15mA as the pumping current. After simulation, the photon density outputs can be plotted as Fig.4. and Fig.5.

From the plot, we could see the response of 15mA model is badly distorted due to the memory length of the model. However, the 10mA model has a much better optical response. Hence we only use 10mA model for our further research.

To see the relationship between the input electrical signal and the output optical signal, I applied an 100MHz sinusoidal signal to the system with no delay and observe the simulation result comes from the photon density output.

In first simulation, I increases the amplitude of the input signal from

0.001mA to 1mA, with 0.001mA as the increasing step. For each step I simulate
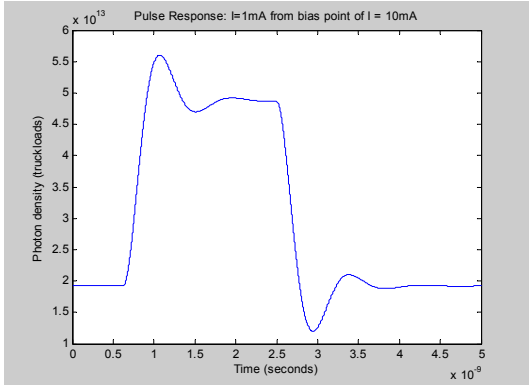

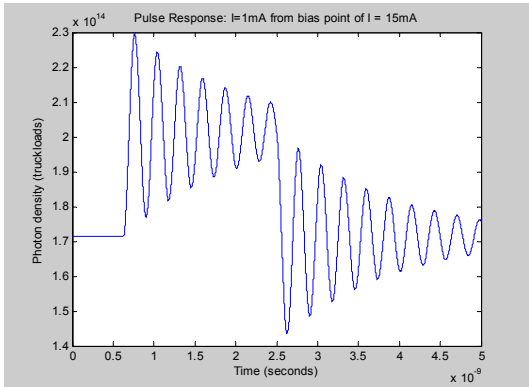Figure 4: 10mA Model Response


Figure 5: 15mA Model Response

once and capture the maximum amplitude. The maximum amplitude of each input signal is also captured. So when the simulation is over, the relationship of the electrical input signal and the optical output signal in terms of amplitude can be plotted as Fig. 7. It can be seen that the output amplitude increases linearly with the input amplitude.

Fig. 6 displays the input and the output sinusoidal signal when the input amplitude is 0.5mA.

There is a time shift between them. This is caused by the delay of the system. But no phase shift is observed. So my second simulation is to find out whether the time delay will change according to the change of input

amplitude. This is achieved by similar simulation design as the first one regarding amplitude. The result (Fig.8) shows that time delay is fixed to 0.1056ns when the input signal's frequency is 100MHz. It won't correspond to any changes of the input amplitude.
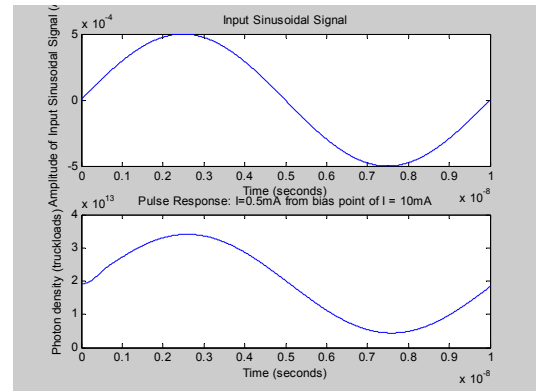

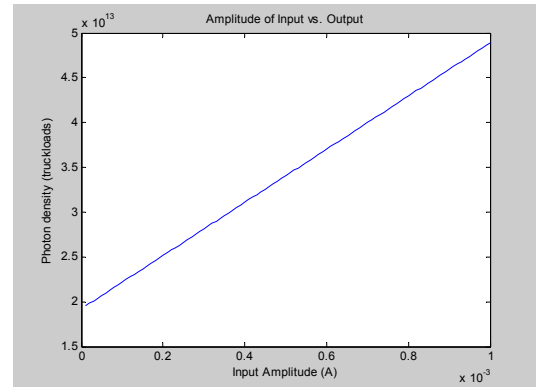Figure 6: Input Electrical Power vs. Output Optical Power
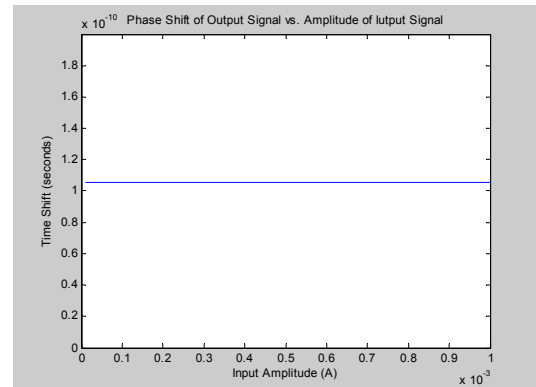

Figure 7: Amplitude Response


Figure8: Time Delay Response

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## Conclusions

From the simulation I prove that this Single Mode Semiconductor Laser Diode Model is useful in simulating the behavior of a Laser Diode.

When working in the linear region, the output amplitude does respond linearly to the input amplitude. But the time shift does not change accordingly to the input amplitude. It's a fixed value provide the input frequency is fixed.

In summary, this project proposes a way to model the behavior of a Semiconductor Laser Diode and the corresponding methods to analyze the working conditions of the Laser Diode.

## Reference

[1] Toby Schaer, Robert Rusnov, Stephen Eagle, Jay Jastrebski, Steven Albanese and Xavier Fernando, "A Dynamic Simulation Model for Semiconductor Laser Diodes", *CCECE 2003 – CCGEI 2003,* Montreal, May/mai 2003.

[2] Gerd Keiser, Optical Fiber Communications third edition, McGraw-Hill, 2000.

[3] S.A. Javro & S.M. Kang, "Transforming Tucker's Linearized Laser Rate Equations to a Form that has a Single Solution Regime", Journal of Lightwave Technology, 1995.

[4] Xavier N. Fernando and Abu B. Sesay, "Higher order Adaptive Filter based Predistortion for Nonlinear Distortion Compensation of Radio over Fiber links", IEEE, 2000

## Appendix

```
% smallsig.m : Linearized stae-space laser diode model

% Rusnov et al. March 2002

% Revised by Guangjian FENG


clear all; close all; echo off


% Set the operating point here

% Operating Point Values, obtained from Simulink Model

n_10 = 1.9531e18;

s_10 = 1.9221e13;

n_15 = 1.9571e18;

s_15 = 1.7141e14;


% Other constants (Javro & Kang)

q = 1.6e-19;

Va = 9e-11;

tn = 3e-9;

tp = 1e-12;

gamma = 0.44;

beta = 4e-4;

N0 = 1.2e18;

g0 = 3e-6;

eta = 0.1;

h = 6.624e-34;

f = 1.997e14;

alpha = 2;

epsilon =0;


% Hand-derived Jacobian matrix


A_10 = [-g0*s_10-1/tn -g0*(n_10 - N0);
gamma*g0*s_10+gamma*beta/tn gamma*g0*(n_10 - N0)-
1/tp]

A_15 = [-g0*s_15-1/tn -g0*(n_15 - N0);
gamma*g0*s_15+gamma*beta/tn gamma*g0*(n_15 - N0)-
1/tp]


% Remaining Matrices

B = [(1/(q*Va)); 0]

C = [0 1]

D = 0


% Generate time vector in a useful range (0 - 1e-8)

[u,t] = gensig('sin', 1e-8, 1e-8, 0.0001e-9);
```

```matlab
% Generate state-space object

sys = ss(A_10,B,C,D);

sys_15 = ss(A_15,B,C,D);

% Simulate Photon Density Output when Input Sinusoidal
Amplitude is 0.5mA on Frequency 10e+8Hz

u=u*5e-4;
y = lsim(sys,u,t);
y = s_10*ones(length(y),1) + y;

% Plot Input Electrical Signal

subplot(2,1,1);
plot(t,u)
xlabel('Time (seconds)');
ylabel('Amplitude of Input Sinusoidal Signal (A)');
title('Input Sinusoidal Signal')

% Plot Output Optical Response

subplot(2,1,2);
plot(t,y)
xlabel('Time (seconds)');
ylabel('Photon density (truckloads)');
title('Pulse Response: I=0.5mA from bias point of I =
10mA');


% Generate a set of Sinusoidal Signals with Increasing
Amplitude and
% Do Simulation. Capture the Amplitude and Time Delay
Value each time

[u,t] = gensig('sin', 1e-8, 1e-8, 0.0001e-9);
count=1;
for i=1:1:100
    I_step = i*1e-5;
    u = u*I_step;
    y = lsim(sys,u,t);
    y = s_10*ones(length(y),1) + y;

    u_A(1,count) = max(u);
    y_A(1,count) = max(y);

    ytemp = y(1:round(length(y)/2),1);
    y_P(1,count) = t(find(ytemp==max(ytemp)))-1e-8/4;


    count = count + 1;
    [u,t] = gensig('sin', 1e-8, 1e-8, 0.0001e-9);
end


% Plot Amplitude Response
figure
plot(u_A,y_A)

xlabel('Input Amplitude (A)');

ylabel('Photon density (truckloads)');

title('Amplitude of Input vs. Output');

% Plot Time Shift Response

figure
plot(u_A,y_P)
axis([0 1e-3 0 2e-10])

xlabel('Input Amplitude (A)');

ylabel('Time Shift (seconds)');

title('Phase Shift of Output Signal vs. Amplitude of Iutput
Signal');
```