CIRCUIT MODELING FOR THE SIMULATION OF SEMICONDUCTOR LASERS

A THESIS

Submitted in partial fulfillment of the requirements for the award of the Degree of Bachelor in Electrical and Electronics Engineering

by

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(HK 2002-3339)

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KOTA KINABALU

2006

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JUDUL: Circuit Modeling For The Simulation of Semiconductor Lasers

IJAZAH: Kejuruteraan Elektrikal Dan Elektronik

SESI PENGAJIAN: 2002/2003

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DECLARATION

I declared that the writings in this thesis are the sole work of mine except for quotations, summaries and references, which have been duly acknowledged.

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CERTIFICATION

This is to certify that the project report entitled "Circuit Modeling For The Simulation Of Semiconductor Lasers" is a bona-fide record of the work done by Khoo Kay Leong under my guidance and supervision.

Prof. Dr. Pukhraj Vaya

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ACKNOWLEDGEMENT

First of all, I would like to thank my supervisor, Prof. Dr. Pukhraj Vaya for his support, patience and guidance throughout different stages of this project work. He is an outstanding researcher, mentor, and tremendous source of motivation. I will always be grateful to him for introducing me to the field of photonics. With his immense knowledge and research background, he has provided me with a strong fundamental knowledge on the physics of semiconductor lasers. The opportunities that he provided me for understanding the intricacies of photonics research have certainly prepared me well for my future endeavors.

I wish to thank and acknowledge useful and informative discussion with Mr. Liau Chung Fan, Senior lecturer, University Malaysia Sabah. I am indebted to him for being my dearest friend and mentor throughout my undergraduate studies. I have enjoyed and benefited from fruitful discussion with my research partner, Mr. Tan Chee Leong. He assisted me a lot on the modeling aspect of this work.

Special thanks go to Dr. M.Ganesh Madhan, Asst. Professor, Anna University for his help in the literature search and his technical expertise. I would like to express my gratitude to Deputy Dean of Academic and Student Affairs, Dr. Patricia Anthony and Program Coordinator, Mr. Khairul for putting effort in securing the much-needed fund for my participation in COMET 2006. My heart is filled with immense gratitude towards Dean of School of Engineering and Information Technology, University Malaysia Sabah, all the professors, lecturers, staffs and my course mates who have supported and encouraged me against difficulties.

Finally, I would like to thank my beloved parents and brothers for their great love and faith in me for all these years. Frequent phone conversations with them have relieved me from homesickness and I could never have endured four years of engineering studies without their continuous support.

My sincere thanks to all of you.

KHOO KAY LEONG

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ABSTRAK

KAEDAH PEMBENTUKAN LITAR MODEL LASER BAGI KAJIAN SIMULASI KE ATAS LASER SEMIKONDUKTOR

Tesis yang ditulis mengupas bagaimana menjalankan kajian simulasi ke atas laser diod heterosimpangan dan laser diod jenis telaga-kuantum. Kaedah pembentukan litar model laser telah disampaikan dalam tesis ini. Kajian simulasi seperti ini membolehkan pemerhatian analitis dijalankan ke atas sifat-sifat struktur laser yang sebenar. Tambahan pula, cara ini dapat memastikan alat laser berfungsi sepenuhnya sebelum alat laser sebenar dipasang siap. Pembentukan litar model laser merupakan kaedah simulasi yang cekap dan tepat kerana tidak melibatkan pengiraan berkomputer yang kompleks. PSPICE telah digunakan untuk selaku model laser yang dirumuskan daripada persamaan kadar. Model laser diod heterosimpangan telah dirumuskan daripada persamaan kadar dan digolongkan kepada dua kumpulan operasi, iaitu monomod dan multimod. Model tersebut terdiri daripada komponen litar diskret. Analisis terperinci telah dijalankan ke atas ciri-ciri isyarat ulang-alik dan isyarat terus. Tambahan pula, model tersebut mengambil kira kesan parasitic, cas-ruangan kapasitans, pemacu litar elektrik dan kesan elektro-optik di dalam lapisan aktif. Respons modulasi, hubungan antara arus dengan kuasa optik dan kesementaraan model laser juga telah dikaji. Untuk memperolehi respons tersebut, parameter pada model laser telah diubah-ubah semasa proses simulasi. Pemalar bagi pancaran spontan didapati memberi kesan kepada kesementaraan model laser seperti mengakibatkan isyarat optik tertunda. Terjadinya puncak resonans yand kedua pada frequensi tinggi berpunca daripada rintangan dalaman pada punca arus. Penjelasan tentang cara menukarkan model laser yang berasaskan isyarat terus kepada yang berasaskan isyarat ulang-alik telah diberi keutamaan dalam tesis ini. Di samping itu, kesan pemampatan pada respons modulasi juga telah dititikberatkan. Model laser diod jenis telaga-kuamtum juga disampaikan dalam tesis ini. Laser jenis ini mempunyai nilai arus ambang yang lebih rendah berbanding laser lain. Arus ambang didapati mengakibatkan isyarat optik tertunda dan terjadinya ayunan pada respons keluaran. Tambahan pula, peningkatan masa yang diambil oleh elektron bagi melalui bahagian pengurungan heterosimpangan berasingan di dalam struktur laser diode jenis telaga-kuantum boleh membawa kesan negatif kepada puncak resonans dan -3db jalur gelombang komunikasi. Kebanyakan keputusan simulasi yang dipersembahkan dalam tesis ini adalah memuaskan. Model laser yang telah ditunjukkan adalah amat berguna dalam rekaan dan simulasi rangkaian gentian optik mikrogelombang dan litar bersepadu optik.

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ABSTRACT

CIRCUIT MODELING FOR THE SIMULATION OF SEMICONDUCTOR LASERS

The main objective of this thesis is to perform simulation studies on double-heterojunction (DH) injection lasers and quantum-well (QW) lasers. Circuit level modeling of these laser models is presented in this thesis. Simulation studies provide analytical observation on the behavior of actual laser structures and to ensure that the device is fully operational before its actual fabrication. The circuit models presented provides a fast and accurate simulation tool with little computational complexity for large and small signal behavior. Rate equation based laser models have been simulated using PSPICE simulator. DH laser model is derived using rate equations for single mode operation and later expanded to multimode operation. The DH laser model consists of mainly discrete components. Detailed analysis is carried out on both large and small signal circuit models. The two port circuit model includes the effect of chip and package parasitics, space-charge capacitance, electrical drive circuit and electro-optical dynamics of the active layer. The modulation response, light-current characteristic and transient behavior of the DH lasers are studied. Simulated response is obtained by varying different parameters of the rate equations. It has been observed that spontaneous emission coefficient contributes significantly to the turn-on delay and damping of relaxation oscillation. The effect of source resistance on the frequency response is also studied; the occurrence of second resonance peak at higher frequency has been observed. Detailed description of linearization performed on large signal model in order to obtain the small signal ac circuit model is also presented. The procedure outlined in this thesis serves as a general guideline for any attempt on linearization of any type of large signal laser circuit models. Finally, the effects of gain compression and various parameters of small signal model on modulation response are also studied. A single mode large signal QW laser model is presented. QW laser demonstrates significant reduction in magnitude of threshold current as compared to conventional semiconductor lasers. Bias current imposes limit on turn on delay and relaxation oscillation of light output response of QW laser. Also, it is demonstrated that increases in carrier transport time across the separate confinement heterostructure (SCH) region has complementary effect on resonance peak and –3db bandwidth of modulation response. The simulation results presented in this thesis agree well with existing published work. The laser model can be applied in the design and simulation of microwave optical fiber link (GHz range), optoelectronic integrated circuits (OEIC) and photonic devices.

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GLOSSARY

AC	Alternate Current
CAD	Computer Aided Design
CCCS	Current Controlled Current Source
CCVS	Current Controlled Voltage Source
DC	Direct Current
DHLD	Double Heterojunction Laser Diode
MQW	Multiple Quantum Well
mA	Milliampere
mV	Millivolt
ns	Nanosecond
OEIC	Optoelectronic Integrated Circuits
QWL	Quantum Well Lasers
R_{in}	Input resistance
SCH	Separate Confinement Heterostructure
SCL	Semiconductor Lasers
SQW	Single Quantum Well
TQW	Three Quantum Well
VCVS	Voltage Controlled Voltage Source
VCVS	Voltage Controlled Voltage Source

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CHAPTER 1

INTRODUCTION

1.1 Motivation

Optoelectronics, namely the integration of photonic and electronic components; is a technology of electronic devices that interacts with light, which may be in the visible spectral region, the infrared or ultraviolet region. In other words, optoelectronics is at the crossroads of electronics and optics. It is being considered as a viable means for overcoming many of the bottlenecks and limitations of purely electronic systems. The most well known example is the optical head of a CD-ROM, in which semiconductor laser and photodetector are used to optically probe compact disc for information. In general, optoelectronic system consists of various photonic components, such as optical source (semiconductor laser), detector (photodiode), optical modulator and transmission medium (fiber optics, holograms and lenses).

Semiconductor laser diode is an important light source in optoelectronic integrated circuits (OEIC's) and photonic devices for applications such as fiber optic communication and optical interconnections. Compared to other types of lasers, it offers a few distinct advantages, namely high efficiency, simplicity of modulation and compact size. For the past 20 years, we have witnessed large amount of research funding and efforts invested in the development of suitable models for optoelectronics devices especially semiconductor laser. The advancement of optoelectronic Computer Aided Design (CAD) tools depends mainly on the continuous improvement of existing model or the development of new models. Motivated by these

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observations, our specific interest here is the simulation of circuit level models for various structures of semiconductor lasers.

1.2 Research objectives

The main aims of the project are to:

- Observe the characteristics of different semiconductor laser structures.
- Perform circuit modeling and simulation on the following semiconductor laser structures:
  - ❖ Double heterojunction injection lasers.
    - Large signal circuit model: single mode and multimode.
    - Small signal circuit model: single mode and multimode.
  - ❖ Quantum well lasers.
    - Large and small signal analysis.

1.3 Thesis overview

Chapter 2 describes different types of semiconductor lasers and provides brief history of various laser modeling approaches and simulators. It also gives a brief overview on circuit modeling of laser diodes and laser light modulation.

Chapter 3 describes the methodology followed in the present project work. Laser circuit models are derived from the well known rate equations. Upon the completion of the circuit models, large and small signal analyses are carried out. Ultimately, verification task on the circuit model is performed. The whole methodology adopted in the project work is outlined on a flow chart.

Chapter 4 elaborates on the implementation of Double-Heterojunction Laser Diode (DHLD) in PSPICE simulator and presents simulation results for the variety of circuit analysis such as DC sweep and transient. Both single mode and multimode large signal circuit models are presented. The results show good agreement with published work.

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Chapter 5 describes in detail the derivation of the small signal circuit model through linearization of the DHLD large signal circuit model. The effect of bias current on the model's frequency response is also studied.

Chapter 6 explains an improved small signal circuit model which incorporates gain compression. Comparison between the frequency response of small signal circuit model with and without gain compression is made.

Chapter 7 describes the simulation of quantum well laser model. The effect of Separate Confinement Heterostructure (SCH) width on the laser model's modulation capability is investigated. The QW laser's turn-on delay is studied as a function of transport time and bias current.

Chapter 8 summarizes the work presented in this thesis. It also outlines future research plans involving the studies of temperature effect on different laser models and analytical studies on optical bistability in bisegmented lasers.

1.4 Scope of project

Develop an understanding on the various equivalent circuit model derived from the rate equations. Computer Aided Design (CAD) tools are used to model the semiconductor lasers. Investigation is carried out to determine how well the proposed model is able to replicate the operating characteristics of actual laser device. The capability of the model is investigated by varying various parameters in the model such as spontaneous coupling factor, β and many more. Experimental data and simulation results from published papers are gathered for validation purposes.

1.5 Outcome of project

Publication: Khoo Kay Leong, Tan Chee Leong & Pukhraj Vaya. 2006. Simulation studies on single mode operation of double-heterojunction injection laser, *Conference on Manufacturing and Electronic Technology, COMET 2006, Universiti Teknologi Malaysia (UTM), Malaysia.*

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- Won 3rd prize for oral thesis presentation in the undergraduate division organized by COMET, 14th-15th January 2006.

Presentation: "Circuit Level Modeling of Quantum Well Lasers", UMS-GIST (Gwangju Institute of Science and Technology, South Korea), *International Symposium on Science and Technology.*

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CHAPTER 2

LITERATURE REVIEW

2.1 Chapter overview

This chapter provides a brief background on the different structures of semiconductor lasers. It also covers the numerous modeling approaches for semiconductor laser, software simulator, different modulation techniques for laser light and the hierarchy of laser circuit model.

2.2 Types of semiconductor laser

Modern laser diodes use a sandwich-like structure of different semiconductor materials to form the p-n junction. The center part of this structure has a lower bandgap and a higher refractive index than the cladding material, thus confining electron–hole pairs by energy barriers. Photons confinement is achieved by total internal reflection. InP is the most common cladding and substrate material for laser emission in IR range. The center layers are made of InGaAsP or other III–V compound semiconductors whose composition and thickness are tailored to obtain optimum laser performance. This type of structure is typically found in Double Heterojunction laser.

A different type of laser structure called quantum wells (QW) structure is only a few nanometers thick active region where photons are produced. The QW bandgap is tailored to give the desired photon wavelength. Multiple quantum wells (MQW) are often used to multiply the gain and to reduce the required carrier density and increasing the differential gain. Distributed feedback (DFB) laser employs a periodic

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longitudinal variation of the refractive index within one layer of the edge-emitting waveguide structure and is widely used for single mode analog applications. Vertical-cavity surface emitting laser (VCSEL) emits light through the bottom and/or top surface of the layered structure. In VCSEL, distance and layer thickness of the two distributed Bragg reflectors (DBR) control the lasing wavelength.

2.3 Various modeling approach for semiconductor lasers

One method for simulating semiconductor lasers is through the use of device level modeling, in which internal physical mechanisms of the laser diode are modeled. These models require multidimensional analysis of spatial behavior, as well as analytical solution of the laser's optical characteristics (Joachim & John, 2000). For instance, MINILASE is a two dimensional Quantum Well laser simulator which combines complex simulation of carrier dynamics, optical field and temperature effects. However, device level modeling is very computational intensive and requires high performance computers. Typically, large numbers of simulations are carried out to verify and optimize the design parameters. Under this kind of circumstances, device level modeling is not an ideal analytical method for simulation studies of semiconductor laser.

Circuit level modeling offers an alternative modeling method. This method can still accurately replicate the operating characteristic of a real laser. Its strength lies in its representation of a particular laser model as an interconnection of discrete circuit elements such as resistor, capacitor and inductor. Circuit level laser model permits simulation of laser characteristics by general purpose circuit analysis program like PSPICE. Table 2.1 shows different circuit models proposed by a number of researchers.

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Table 2.1: Highlights of circuit level semiconductor laser models

Researchers	Year	Features of laser model
Katz	1981	Rate equation based, small signal RLC circuit
Habermayer	1981	Effects of multimode
R.S. Tucker	1981	Large signal single mode DHLD
Harder	1982	Noise sources
Kan and Lau	1992	Small signal Quantum well laser model, well-barrier
Bewtra	1995	Thermal equivalent circuit
Lu	1995	Large signal Quantum well laser model, carrier
Y.Su	1996	Modeling of VCSEL static L-I characteristic
Tsou and Pulfrey	1997	Three level rate equations for Quantum Well lasers (Inclusion of gateway states)

The implementation of such models is usually not straight forward and requires the ability to adapt the rate equations (in case of laser diode) into their corresponding equivalent circuit elements. With this new approach, we can simulate the electrical and optical properties of a laser diode and perform both DC and transient simulations of the device. In many cases, these models are constructed as subcircuits from primitive elements such as nonlinear controlled sources, resistors and capacitors. Thus, the laser model can be easily implemented. There are unique advantages offered by circuit modeling. First, it facilitates the simulation of complicated input signal. Second, the rate equation parameters are easily identifiable within the circuit, and third, parameter variation can be performed and its corresponding effects are observable in the laser output. Moreover, parasitic and load networks can be incorporated into the laser model.

2.4 Simulator

With the advent of computer aided design tools (CAD); modeling, simulation and verification of laser models can be carried out in advance of actual fabrication. There are number of existing optoelectronic design tools, such as SABER, where we can take advantage of its robust behavioral modeling language, MAST. It is mainly used

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for analog, mixed-signal and mixed-technology applications. Another simulator called iFROST supports event-driven simulation of optoelectronic data links, while iSMILE incorporates circuit-level photonic device models into SPICE-like simulation environment.

Physical device models based on complex differential equations can be easily implemented in the object-oriented circuit simulator *f* REEDA, which is a circuit simulator that provides simplified environment for model development of all kinds, be it electrical, electromagnetic, thermal, or optical. In its object-oriented design, all kinds of elements can be considered as objects, and all these elements are connected to each other just like nodes and edges in a circuit graph. Analog Behavioral Modeling (ABM) feature of PSPICE allows for behavioral modeling of complex devices and circuits through the use of built-in or user-defined functions. ABM tools model devices, circuits, and systems as a set of algebraic or differential equations which are subsequently solved in DC, AC or transient analysis.

Development of accurate laser models and the ability to easily implement them in circuit simulators in a compact and accurate way is greatly desirable.

2.5 Direct modulation of semiconductor laser

Direct modulation of the light output intensity of laser diode is performed by superimposing a signal current on the bias current as shown in Figure 2.1 (Nagarajan *et al.* 1991).

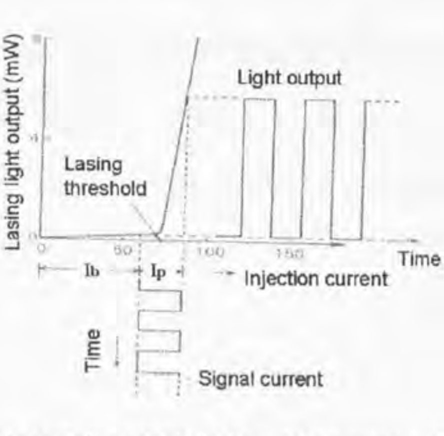

Figure 2.1: Direct intensity modulation of semiconductor laser

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