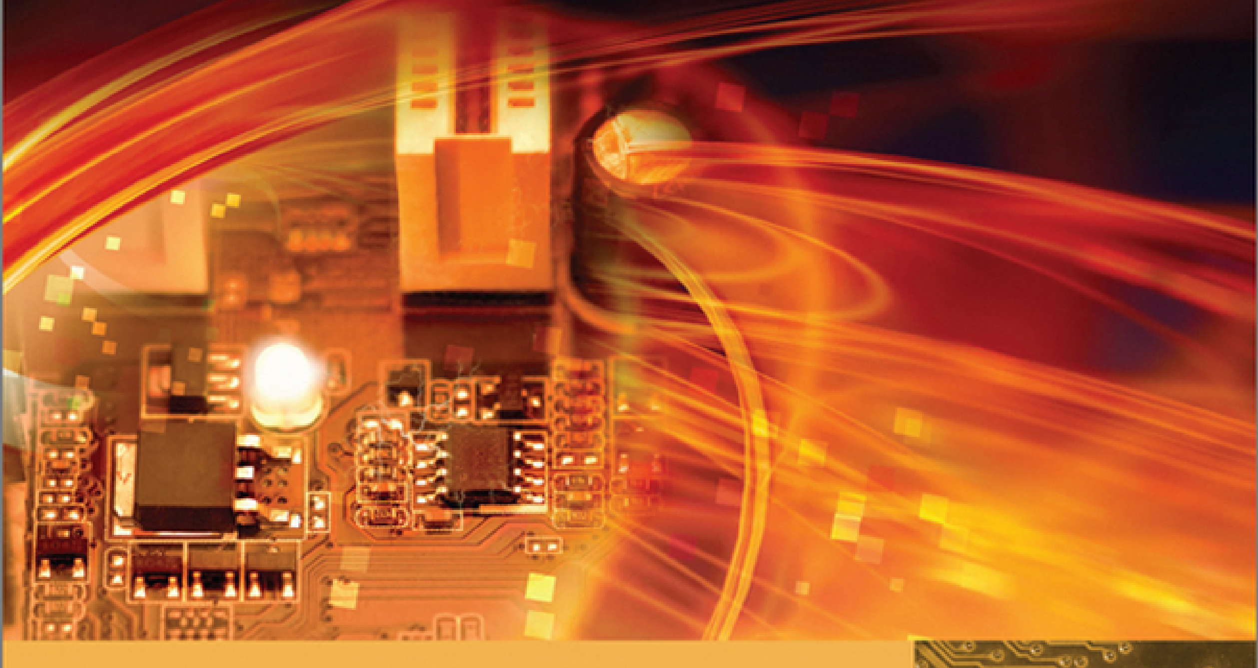
Optoelectronic Integrated Circuit Design and Device Modeling

Jianjun Gao



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Contents

Preface

This textbook is written for the beginning user of optoelectronic integrated circuit (OEIC) design. My purpose is as follows:

- To introduce the basic concepts of optoelectronic devices
- To describe the modeling technique for optoelectronic devices and electronic devices used in high-speed optical systems
- To provide advanced optical transmitter and receiver front-end circuit design techniques.

As we know, state-of-the-art computer-aided design (CAD) methods for OEICs rely heavily on models of real devices. When CAD tools are properly utilized, it is often possible to produce successful designs after only one design iteration. Given the considerable time and cost associated with unnecessary design revisions, CAD tools have proven themselves invaluable to electronic designers. Our primary objective with the present book is to bridge the gap between semiconductor device modeling and IC design by using CAD tools.

Appropriate for electrical engineering and computer science, this book starts with an introduction of an optical fiber communication system, and then covers various lasers, photodiodes, and electronic devices modeling techniques, and high-speed optical transmitter and receiver design. Even for those without a good microwave background, the reader can understand the contents of the book. The presentation of this book assumes only a basic course in electronic circuits as a prerequisite.

The book is intended to serve as a reference book for practicing engineers and technicians working in the areas of radio-frequency (RF), microwave, solid-state devices, and optoelectronic integrated circuit design. The book should also be useful as a textbook for optical communication courses designed for senior undergraduate and first-year graduate students. Especially in student design projects, we foresee that this book will be a valuable handbook as well as a reference, both on basic modeling issues and on specific optoelectronic device models encountered in circuit simulators. The reference list at the end of each chapter is more elaborate than is common for a typical textbook. The listing of recent research papers should be useful for researchers using this book as a reference. At the same time, students can benefit from it if they are assigned problems requiring reading of the original research papers.

About the Author

Jianjun Gao (M'05–SM'06) was born in Hebei Province, P.R. China, in 1968. He received BEng and PhD degrees from Tsinghua University, in 1991 and 1999, respectively, and an MEng degree from the Hebei Semiconductor Research Institute, in 1994.

From 1999 to 2001, he was a Post-Doctoral Research Fellow at the Microelectronics R&D Center, Chinese Academy of Sciences, developing a PHEMT optical modulator driver. In 2001, he joined the School of Electrical and Electronic Engineering, Nanyang Technological University (NTU), Singapore, as a Research Fellow in semiconductor device modeling and wafer measurement. In 2003, he joined the Institute for High-Frequency and Semiconductor System Technologies, Berlin University of Technology, Germany, as a Research Associate working on the InP HBT modeling and circuit design for high-speed optical communication. In 2004, he joined the Electronics Engineering Department, Carleton University, Canada, as Post-Doctoral Fellow working on semiconductor neural network modeling techniques. From 2004 to 2007, he was a Full Professor with the Radio Engineering Department at Southeast University, Nanjing, China. Since 2007, he has been a Full Professor with the School of Information Science and Technology, East China Normal University, Shanghai, China. He has authored *RF and Microwave Modeling and Measurement Techniques for Field Effect Transistors* (USA SciTech Publishing, 2009). His main areas of research are characterization, modeling, and wafer measurement of microwave semiconductor devices, optoelectronic devices, and high-speed integrated circuit for radio-frequency and optical communication.

Dr Gao is currently a member of the editorial board of *IEEE Transactions on Microwave Theory and Techniques*.

Home page: http://faculty.ecnu.edu.cn/gaojianjun/info_eng.html.

Nomenclature

Units

nm	nanometer, one-billionth of a meter (= 10^{-9} m)
µm	micrometer, one-millionth of a meter (= 10^{-6} m)
fs	femtosecond, one-millionth of a billionth of a second (= 10^{-15} s)
ps	picosecond, one-thousandth of a billionth of a second (= 10^{-12} s)
ns	nanosecond, one-billionth of a second (= 10^{-9} s)
GHz	gigahertz, 1 billion vibrations per second (= 10^{9} Hz)
THz	terahertz, 1000 billion vibrations per second (= 10^{12} Hz)
mW	milliwatt, one-thousandth of a watt (= 10^{-3} W)
Mb/s	1 million bits per second (= 10^{6} bits per second)
Gb/s	1 billion bits per second (= 10^{9} bits per second)
Tb/s	1000 billion bits per second (= 10^{12} bits per second)
c	speed of light in vacuum, 300 million kilometers per second (= 3×10^{8} m/s)
h	Plank's constant (= 6.626×10^{-34} J s)
k	Boltzmann's constant (= 1.38×10^{-23} J/K)
fF	femtofarad, one-billionth of a farad (= 10^{-15} F)
pF	picofarad, one-thousandth of a billionth of a farad (= 10^{-12} F)
nF	nanofarad, one-billionth of a farad (= 10^{-9} F)
nH	nanohenry, one-billionth of a henry (= 10^{-9} H)
pH	picohenry, one-thousandth of a billionth of a henry (= 10^{-12} H)

Abbreviations

2-D	two-dimensional
AC	alternating current

AGC	automatic gain control
AlGaAs	aluminum gallium arsenide
APD	avalanche photodiode
BER	bit error rate/ratio
BFL	buffered FET logic
BH	buried heterostructure
BJT	bipolar junction transistors
CAD	computer-aided design
CPW	coplanar waveguide
CW	continuous wave
DA	distributed amplifier
DBR	distributed Bragg reflector
DC	direct current
DCFL	direct-coupled FET logic
DFB	distributed feedback lasers
DH	double heterojunction
DMUX	demultiplexer
DSM	dynamic-single-mode
DWDM	dense wavelength division multiplexing
EA	electroabsorption
ECL	emitter coupled logic
ER	extinction ratio
FM	frequency modulation
FP	Fabry–Perot
GaAs	gallium arsenide
GMIC	optoelectronic glass microwave integrated circuit
GRIN-SCH	graded index separate confinement heterostructure
HB	harmonic balance
HBT	heterojunction bipolar transistor
HEMT	high electron mobility transistor
HOEIC	hybrid optoelectronic integrated circuits
HZ	high-impedance
IL	insertion loss
IM	intensity modulation
IMD	intermodulation distortion
IM-DD	intensity modulation direct-detection
InP	indium phosphide
I/O	input/output
ITS	intelligent transport system
I–V	current–voltage
laser	light amplification by stimulated emission of radiation
LD	laser diode

LED	light-emitting diode
$LiNbO_3$	lithium niobate
MBE	molecular beam epitaxy
MESFET	metal semiconductor field-effect transistor
MMAC	multimedia mobile access communication
MOCVD	molecular organic chemical vapor deposition
MOEIC	monolithic optoelectronic integrated circuit
MOSFET	metal oxide semiconductor field-effect transistor
MQW	multiquantum well
MSM	metal–semiconductor–metal
MUX	multiplexer
M–Z	Mach–Zehnder
NRZ	nonreturn-to-zero
OEIC	optoelectronic devices and integrated circuit
PD	photodiode/photodetector
$P–I$	power-current
PIC	photonic integrated circuits
QW	quantum-well
RF	radio-frequency
RFIC	radio-frequency integrated circuit
RIN	relative intensity noise
RMS	root mean square
RZ	return-to-zero
SAM	separate-absorption-and-multiplication
SCFL	source-coupled FET logic
SCH	separate confinement heterojunction
SCM	subcarrier multiplexing
SCR	space-charge region
SDFL	Schottky diode FET logic
SI	semi-isolation
SiGe	silicon germanium
SLM	single-longitudinal-mode
SMSR	submode suppression ratio
SNR	signal-to-noise ratio
SPICE	simulation program with integrated circuit emphasis
SQW	single quantum well
TDM	time-division multiplexer
TEN	terminal electrical noise
TIA	transimpedance amplifier
TJS	transverse junction stripe
TZ	transimpedance
UV	ultraviolet

VCSEL	vertical-cavity surface-emitting lasers
VNA	vector network analyzer
VSWR	voltage standing wave ratio
WDM	wavelength division multiplexing

1

Introduction

The purpose of this chapter is to give an overview of the field of optical communications, and modeling and simulation methods of optoelectronic integrated devices and circuits. The first section of the chapter describes why there are fundamental reasons why optics is attractive for use in communications; the most important components such as the optical transmitter, fiber, and receiver are introduced briefly. In the second section, the conventional computer-aided design (CAD) methods for optoelectronic devices and integrated circuits (ICs) are introduced.

1.1 Optical Communication System

The recent explosive growth of data traffic has stimulated the demand for high-capacity information networks. The data need to be transmitted from one place to another at high speed. There are essentially four possible methods to transmit these data [1, 2, 3]:

1. Free-space radio-frequency (RF) transmission
2. Free-space optical transmission
3. RF propagation over a fixed transmission line
4. Optical propagation over a fixed fiber-optic transmission line.

Free-space RF transmission is flexible and cheap, but it cannot support large (10 Gb/s) bandwidths and requires fairly large power to transmit over long distances. It is also relatively easy to intercept the transmitted signal, although with sufficient encryption it can be essentially impossible to decode. Free-space optical transmission is also quite flexible, but the signal quality and propagation distance are weather-dependent. Standard RF signal propagation over coaxial cable is simple to integrate with standard electronics and is ideal for relatively short distances and low data rates. Fiber-optic links

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are being used increasingly to replace conventional guided-wave methods of conveying RF signals. Fiber-optical signal distribution is known to possess advantages over conventional signal distribution in cases where the signal must be transmitted over long distances, where signal security or low interference is desired, or where the size, weight, or cost of the distribution hardware is important. Fiber-optical transmission systems can replace normal coaxial or hollow waveguide signal distribution systems if the special characteristics of the electrooptical transducers can be tolerated. An additional advantage that makes millimeter-wave desirable for fiber radio systems is that these frequencies are highly attenuated by water molecules and oxygen in the atmosphere. This can be exploited to limit signal propagation to within the proximity of a picocell, as required for wireless secure communication and for frequency reuse.

Fiber-optic communication is a method of transmitting information from one place to another by sending pulses of light through an optical fiber. The light forms an electromagnetic carrier wave that is modulated to carry information. Optical communication systems have been the mainstream information transmission systems in past decades and are still dominant today thanks to the invention and development of broadband semiconductor lasers, low-loss fibers, fast photodetectors, and other high-quality optoelectronic components. The fiber-optic link has many advantages, which include tremendous available bandwidth ($\sim$100 THz), very low transmission loss, immunity to electrical disturbance, and so on; all of this makes a fiber-optic link the preferred transmission solution in many applications.

Figure 1.1 shows a possible scheme for a 40 Gb/s optical transmission system. It requires several high-speed ICs having a bit rate of 40 Gb/s. In the transmitter, a

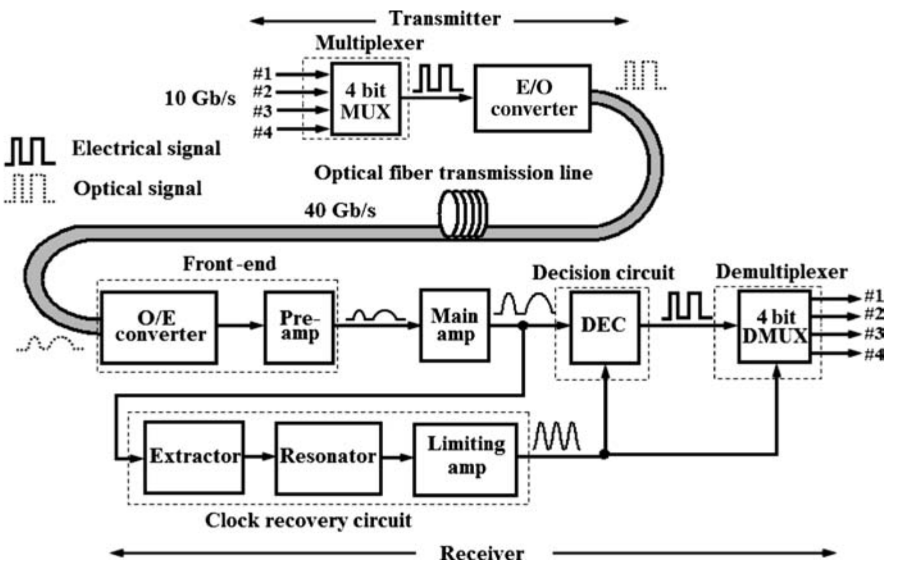

Figure 1.1 Schematic diagram of 40 Gb/s optical fiber transmission configuration.

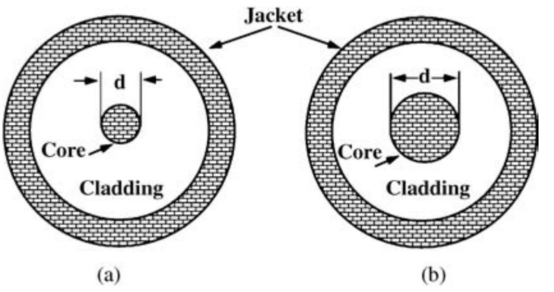

Figure 1.2 Cross-section of optical fiber: (a) single mode; and (b) multimodel.

time-division multiplexer (MUX) combines several parallel data streams (four 10 Gb/s streams in Figure 1.1) into a single data stream with a high bit rate of 40 Gb/s. In the receiver, a demultiplexer (DMUX) splits the 40 Gb/s data stream back into the original four low bit rate streams. The MUX and DMUX are digital medium-scale ICs, which must achieve 40 Gb/s operation with suitably low power dissipation. In the receiver, the extremely small current signal generated by a photodiode is converted into a voltage signal and amplified by a low-noise preamplifier and succeeding main amplifiers having automatic gain control (AGC). The output voltage swing of the amplifier is kept constant, independent of the input signal level. Nevertheless, regeneration, performed by a decision circuit and a clock recovery circuit (composed of a differentiator, rectifier, microwave resonator, and limiting amplifier), is still needed to reduce the timing jitter produced by the cascaded amplifiers. The transmitter and receiver ICs, except for the clock recovery circuit, require broadband operation from near DC to the maximum bit rate with good eye openings.

Compared to the conventional communication system, the difference here is that the communication channel is an optical fiber cable. Figure 1.2 shows the cross-section of single-mode and multimode optical fibres. The cable consists of one or more glass fibers, which act as waveguides for the optical signal (light). In its simplest form an optical fiber consists of a cylindrical core of silica glass surrounded by a cladding whose refractive index is lower than that of the core. Fiber optic cable is similar to electrical cable in its construction, but provides special protection for the optical fiber within. For systems requiring transmission over distances of many kilometers, or where two or more fiber optic cables must be joined together, an optical splice is commonly used.

In multimode fiber, the light is guided by the almost perfect reflection at the interface between the core and cladding. Like multimode optical fibers, single-mode fibers do exhibit modal dispersion resulting from multiple spatial modes, but with narrower modal dispersion. Single-mode fibers are therefore better at retaining the fidelity of each light pulse over long distances than multimode fibers. For these reasons, single-mode fibers can have a higher bandwidth than multimode fibers. Multimode fiber has significantly higher loss (due to modal dispersion) than single-mode fiber and is therefore only used for short distance communications such as within a building or on a corporate campus. All long-distance communications utilize single-mode fiber and laser light sources. In its simplest form an optical fiber consists of a cylindrical core of silica glass surrounded by a cladding whose refractive index is lower than that of the core.

Advantages of the optical fiber are as follows:

- Low attenuation, large bandwidth allowing long distance (>100 km) at high bit rates (>10 Gb/s)
- Small physical size
- Low physical mass, low material cost
- Cables can be made nonconducting, thus eliminating electromagnetic interference and shock hazards and providing electrical isolation
- Negligible crosstalk between fiber channels in the same cable
- High security, since tapping is very difficult
- Upgrade potential to higher bit rates is excellent.

Because of the rapid growth of capacity requirement on long-distance transmission, fiber-optic telecommunications is advancing into high data rate and wavelength division multiplexing (WDM) [4, 5]. WDM, by which multiple optical channels can be simultaneously transmitted at different wavelengths through a single optical fiber, thus multiply the capacity of the link (as shown in Figure 1.3). The advantages of WDM systems are: transmission capacity increase per fiber, system cost reduction, simultaneous transmission of different modulation-scheme signals, and service channel expandability after fiber installation. These are the reasons why WDM technology is expected to be widely applied to systems in various fields of communications. In WDM system design, performance of optical multi/demultiplexers (MUX, DEMUX) should be the primarily consideration, together with fibers, light sources, and photodetectors.

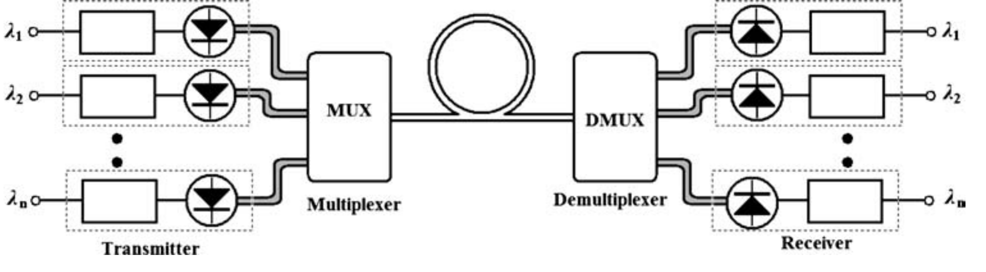

Figure 1.3 Fundamental configuration for WDM transmission.

Radio-frequency (RF) or microwave subcarrier multiplexing has recently emerged as a potentially important multiplexing technique for future high-capacity lightwave systems. Optical subcarrier multiplexing (SCM) is a method for multiplexing many

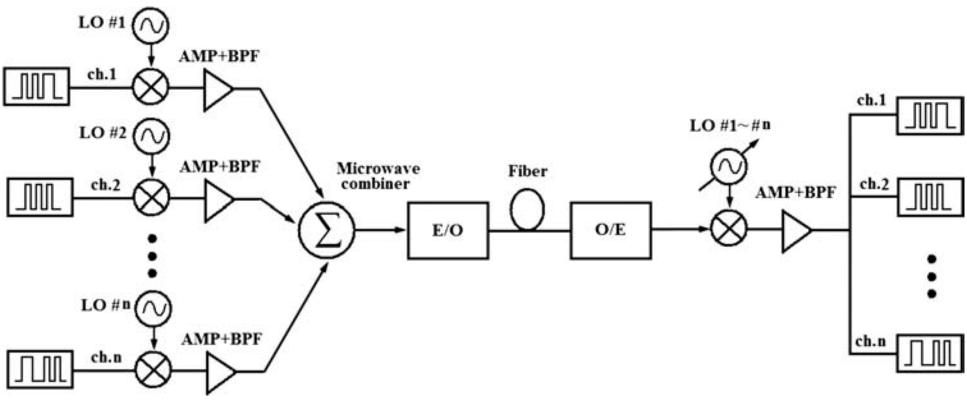

Figure 1.4 Basic SCM system configuration.

different fiber-optic-based communication links into a single uplink fiber [6]. SCM is a scheme where multiple signals are multiplexed in the radio-frequency (RF) domain and transmitted by a single wavelength. The basic configuration of an SCM system is shown in Figure 1.4. A number of baseband analog or digital signals are first frequency division multiplexed by using local oscillators (LOs) of different radio frequencies. The upconverted signals are then combined to drive a high-speed light source. The LO frequencies are the so-called subcarriers in contrast to the optical carrier frequencies. A significant advantage of SCM is that microwave devices are more mature than optical devices; the stability of a microwave oscillator and the frequency selectivity of a microwave filter are much better than their optical counterparts. In addition, the low phase noise of RF oscillators makes coherent detection in the RF domain easier than optical coherent detection, and advanced modulation formats can be applied easily.

1.2 Optoelectronic Integrated Circuit Computer-Aided Design

Intense research to develop and expand the capabilities of fiber-optic technology is under way. The outstanding progress made in optical fiber transmission systems has been largely dependent on newly developed optical and electronic semiconductor devices. To realize high-bit-rate systems, high-speed transmitter and receiver circuits are in great demand, and the development of monolithic ICs, which have higher performances and multiple functions, is indispensable. The gigabit optical transmission systems must not only be high speed but also compact, cost effective, and highly reliable, and must minimize both power consumption and temperature rise, which increase with higher transmission speeds. One of the most effective ways to achieve such a system is with gigabit IC technology. Driver circuits and preamplifiers, which are directly connected to optical devices, are among the key components.

The proliferation of optical and fiber-optic communications has created a need for efficient and accurate CAD tools for the design of optoelectronic integrated circuits and systems. In the electronic world, highly advanced CAD tools exist for the design, analysis, and simulation of nearly every aspect of integration, ranging from process to device to circuit to system. The application of modern CAD tools offers an improved approach. As the sophistication and accuracy of these tools improve, significant reductions in design cycle time can be realized. The goal is to develop CAD tools with sufficient accuracy to achieve first pass design. The CAD tools need to be improved until the simulated and measured RF performance of the component being designed are in good agreement. This will permit the design to be completed, simulated, and fully tested by an engineer working at a computer workstation before fabrication is implemented. In order to achieve this goal, improved accuracy CAD tools are required.

The state of the CAD methods for active optoelectronic circuits rely heavily on models of real devices. There are two kinds of commercial optoelectronic device and integrated circuit CAD software: physical-based and equivalent-circuit-based CAD software. The physical-based CAD software, as a starting point of analysis, considers fundamental equations of transport in semiconductors. The equivalent-circuit-based CAD software addresses the issue of what needs to be known about the device in addition to its equivalent circuit to predict the performance. The model permits the RF performance of a device or integrated circuit to be determined as a function of process and device design information and/or bias and RF operating conditions. The equivalent circuit device models must be based upon accurate parameter extraction from experimental data. The model permits the RF performance of a device or integrated circuit to be determined as a function of process and device design information and/or bias and RF operating conditions. Figure 1.5 shows the flowchart for an ideal

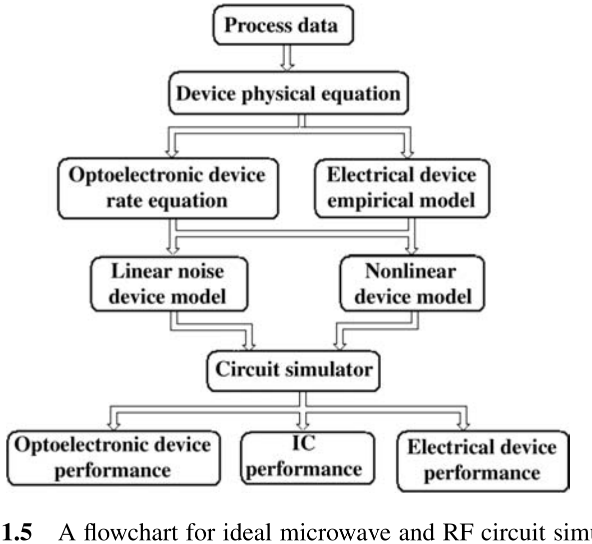

Figure 1.5 A flowchart for ideal microwave and RF circuit simulator.

optoelectronic circuit simulator. Such an integrated simulator allows both the active devices and passive elements to be optimized, based upon the parameters accessible in the fabrication process.

1.3 Organization of This Book

We will spend the rest of this book trying to convey the basic operation mechanism of the key components of high-speed optical communication. The focus will be on how to build the linear, nonlinear, and noise models for optoelectronic devices (including lasers and photodiodes) using physical rate equations and how to design optimum laser/modulator driver and receiver front-end circuits using microwave matching techniques.

In Chapter 2, the physical structure and basic concept of the most commonly used semiconductor laser diodes have been discussed. Based on the rate equations in the active region, the small signal modulation, large signal modulation, and noise performance of laser diode are formulated, and the corresponding measurement techniques are introduced.

Chapter 3 presents the rate-equation-based modeling and parameter extraction techniques for semiconductor lasers. By using the microwave active device modeling concept, the rate equation model parameters can be determined. The standard double herojunction semiconductor lasers and single quantum-well lasers are used as examples. The model parameter extraction techniques for the extrinsic elements, intrinsic elements, and rate equations model parameters are described in more detail.

In Chapter 4, we introduce the physical structure and operation concept of the commonly used photodiodes (such as PIN PD, APD, and MSM PD). The small-signal modeling and parameter extraction method are described.

The high-speed electrical devices such as field effect transistor (FET), heterojunction bipolar transistor (HBT), and metal oxide semiconductor FET (MOSFET) are very attractive for a high-speed optoelectronic integrated circuit. In Chapter 5, the basic physical structures and operation concepts of various semiconductor devices are introduced, and the corresponding small-signal, large-signal, and noise modeling and parameter extraction methods are described briefly.

The laser/modulator driver and receiver front-end are two key components of high-speed optical communication systems. Chapters 6 and 7 deal with the optimum design of 10 Gb/s to 40 Gb/s high-speed laser/modulator driver and receiver front-end integrated circuits based on different semiconductor technologies. The passive peaking techniques, which include inductance and capacitance techniques for extending bandwidth and minimizing the noise performance for the driver and receiver, are described in more detail.

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2

Basic Concept of Semiconductor Laser Diodes

2.1 Introduction

The key elements of microwave photonic systems are optical sources capable of fast modulation, suitable transmission media, and fast optical detectors or optically controlled microwave devices. The development of the first lasers, including in 1960 both the pulsed ruby laser at Hughes Research Laboratories and the continuously operating helium neon laser at Bell Laboratories, can be said to have started the optical communications era [1]. The theoretical and practical foundations for this development were made by the American Charles Townes and the Russians Alexander Prokhorov and Nikolay Basov, who shared the Nobel Prize for Physics in 1964 for their work.

Most fiber-optic communication systems use semiconductor lasers (light amplification by the stimulated emission of radiations) as an optical source because of their superior performance compared with LEDs (light-emitting diodes). As the networks evolve in complexity and sophistication, these lasers must meet increasingly demanding performance specifications: lower power dissipation, higher bandwidth, lower chirp, greater tunability, less temperature sensitivity, and lower noise, wide range of wavelengths, and monolithic integration with other devices. Furthermore, semiconductor lasers are critical components in applications such as optical fiber communications, optical memories, sensors, printers, optical information processing, pumping sources, device processings, and medical inspection. Thus, semiconductor lasers exhibited versatile properties ranging from multimode laser structures mainly used for high-power applications to single-mode laser devices for information technologies [2, 3, 4, 5, 6, 7]. To design such lasers, it is important to understand better the physical device operation, and to be able to tailor and optimize design parameters. Commercial LEDs are only capable of 1 GHz maximum modulation speeds because of slow carrier recombination, limiting them to applications in short-haul optical communication links.

These lasers use semiconductors as the lasing medium and are characterized by specific advantages, such as the capability of direct modulation in the gigahertz region, small size and low cost, the capability of monolithic integration with electronic circuitry, direct pumping with conventional electronic circuitry, and compatibility with optical fibers. Laser diodes (LDs) are more powerful and operate at faster speeds than LEDs, and they can also transmit light farther with fewer errors, have a narrower spectrum, and can couple more power into a fiber. Table 2.1 shows the features comparison of LED and LD.

Table 2.1 Comparison of LED and LD.

Feature	LED	LD
Emitted light	Incoherent	Coherent
Optical spectrum	Wide (30–60 nm)	Narrow (2–4 nm)
Modulation speed	Less than 1 GHz	Up to 10–40 GHz
Threshold current	High	Low
Transmission distance	Short	Long
Output power	Low	High
Cost	Low	High

Depending on the application, it is preferable that laser diodes have some of the following features:

1. Operating at two low-absorption windows for long-distance communication (1.31 μm and 1.55 μm)
2. High output optical power
3. Low threshold current
4. Fast response time
5. High reliability and low cost
6. Easy-to-direct modulation and external modulation.

In this chapter, we will introduce the basic concept of the laser diodes first and then the most commonly used semiconductor laser diodes, such as FP (Fabry–Perot) cavity lasers, QW (quantum-well) lasers, DFB (distributed feedback) laser, and VCSEL (vertical-cavity surface-emitting laser), have been introduced. The small signal modulation, large signal modulation, and noise performance of laser diodes are analyzed based on the rate equations.

2.2 Basic Concept

Although there are various types of semiconductor diode laser, the basic concepts are similar. The first diode lasers were made in the early 1960s and were very similar to light-emitting diodes. However, whereas light from an LED is spontaneously emitted radiation, laser diodes emit light via stimulated emission [8, 9, 10, 11, 12, 13]. In this section, we will introduce three types of interaction between atom and photon: absorption, spontaneous emission, and stimulated emission.

2.2.1 Atom Energy

As we know, all matter is made up of atoms, which essentially consist of a positively charged nucleus and negatively charged electrons round it in fixed orbits. The energy levels of atoms describe the quantum mechanical requirement that microscopic particles have discrete energy values. A given electron in an atom has an orbit of lowest energy that it can occupy, called the ground state. If it is in an orbit with a higher energy, it is said to be in an excited state. As the atoms are brought closer together their electron orbits overlap and hence the discrete energy levels of the free atoms turn into energy bands in the solid phase. The lowermost, almost fully occupied band is called the valence band; the uppermost band, completely empty or partially filled, is called the conduction band. In the semiconductor ground state, all of the available valence electrons share the valence band and none occupy the conduction band; the valence and conduction bands are separated by an energy gap E_g (as shown in Figure 2.1(a)). The difference between insulators and semiconductors is only the forbidden band gap between the valence band and conduction band. The term 'band gap' refers to the energy difference between the top of the valence band and the bottom of the conduction band; electrons are able to jump from one band to another (as shown in Figure 2.1(b)).

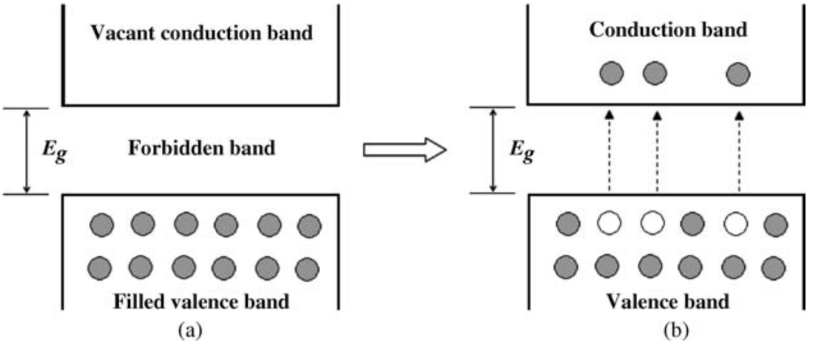

Figure 2.1 Energy bands in a semiconductor.

Under normal thermodynamic equilibrium, the populations of the energy level E_i will be governed by the Boltzmann relation

$$N_i = N \exp\left(-\frac{E_i}{kT}\right) \tag{2.1}$$

where $N_i (i = 1, 2, \ldots, n)$ is the population of level E_i, $k = 1.38 \times 10^{-23}$ J/K is the Boltzmann constant, and T is the temperature in kelvin. Figure 2.2 shows the

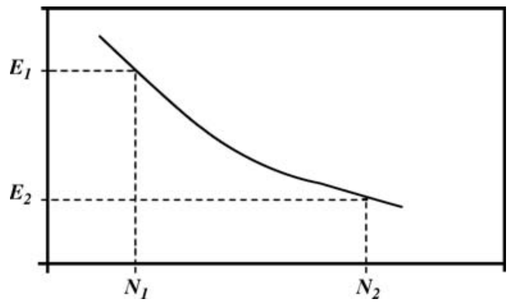

Figure 2.2 The population distribution versus energy level.

population distribution versus energy level. It can be found that population decreases rapidly with an increase of the energy level.

In equilibrium, the charge carriers occupy their lowest energy states, with electrons at the bottom of the conduction band and holes at the top of the valence band. In order to conduct electricity, electrons have to be excited from the valence band into the conduction band, and it requires a specific minimum amount of energy for the transition. The required energy differs with different materials.

2.2.2 Emission and Absorption

Absorption occurs when a photon of just the right energy for a particular transition encounters an atom in the ground state, and causes the atom (or, rather, one of the atom's electrons) to jump into an excited state. The energy of the excited state E_2 equals that of an electron in the ground state E_1 plus that of the incident photon (as shown in Figure 2.3(a)). If the incident light energy is hc/λ (where h is Plank's constant, c is optical velocity, and λ is optical wavelength), the energy of the excited state can be expressed as follows:

$$E_2 = E_1 + hc/\lambda \tag{2.2}$$

Under these conditions, the population of level E_2 is smaller than that of the ground state, level E_1. When a photon is incident on this material, it may either be absorbed or stimulated. The probability for these processes depends on the internal properties of the atoms, the intensity of the radiation, and the population difference between the two energy levels.

Spontaneous emission is when an excited atom spontaneously returns to the ground state, emitting a photon in the process (as shown in Figure 2.3(b)). In the case of spontaneous emission, photons are emitted in random directions with no phase relationship among them. The properties of spontaneous radiation are as follows: wide spectral width, low intensity, poor directiveness, and incoherence, which make it impossible to use LEDs as light sources for long-distance communication links.