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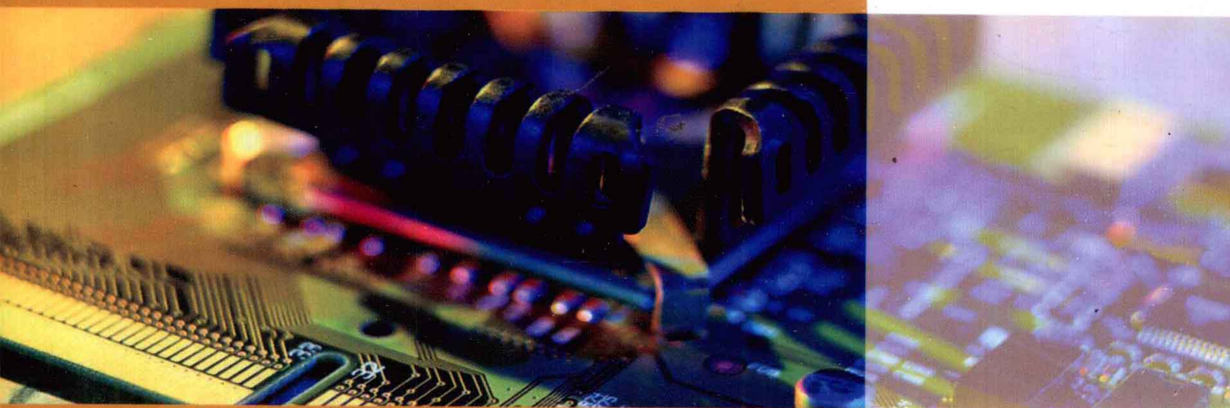
# Optoelectronic Integrated Circuit Design and Device Modeling

# 光电集成电路设计与器件建模

（英文版）

Jianjun Gao



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# 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 (= $3 \times 10^{8}$ m/s) |
| $h$ | Plank's constant (= $6.626 \times 10^{-34}$ J s) |
| $k$ | Boltzmann's constant (= $1.38 \times 10^{-23}$ 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 |

# Contents

# 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

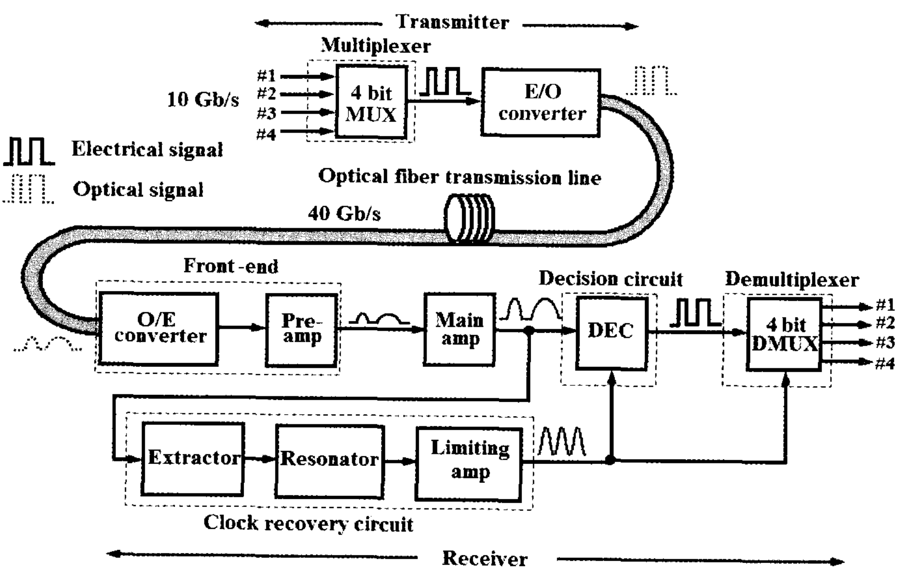


**Figure 1.1** Schematic diagram of 40 Gb/s optical fiber transmission configuration.

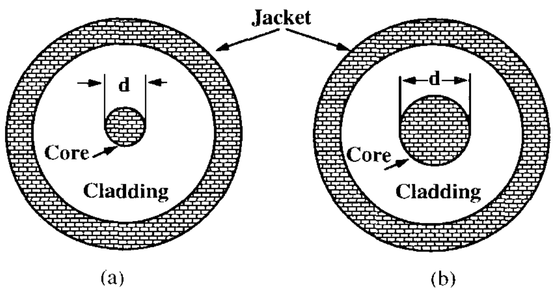


**Figure 1.2** Cross-section of optical fiber: (a) single mode; and (b) multimodel.

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