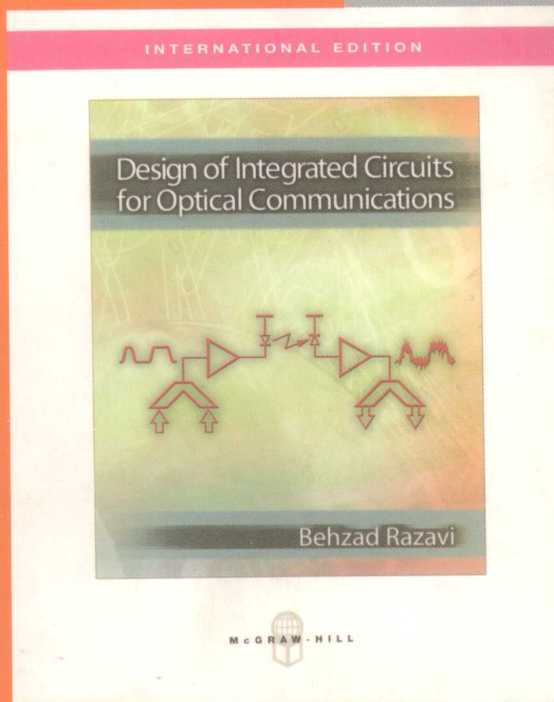
McGraw Hill Education

国外大学优秀教材——微电子类系列（影印版）

Behzad Razavi

光通信集成电路设计



清华大学出版社

国外大学优秀教材——微电子类系列（影印版）

光通信集成电路设计

Design of Integrated Circuits for Optical Communications

Behzad Razavi

清华大学出版社
北京

Behzad Razavi
Design of Integrated Circuits for Optical Communications
EISBN: 0-07-082258-9

图书在版编目(CIP)数据

光通信集成电路设计=Design of Integrated Circuits for Optical Communications/罗扎威(Razavi,B.)著. —影印本. —北京: 清华大学出版社, 2005.5
(国外大学优秀教材——微电子类系列(影印版))
ISBN 7-302-10720-3

Ⅰ. 光… Ⅱ. 罗… Ⅲ. 光通信—集成电路—电路设计—高等学校—教材—英文 Ⅳ. TN929.1

中国版本图书馆 CIP 数据核字(2005)第 023936 号

出 版 者: 清华大学出版社　　**地　　址**: 北京清华大学学研大厦
http://www.tup.com.cn　　**邮　　编**: 100084
社 总 机: 010-62770175　　**客户服务**: 010-62776969
责任编辑: 田志明
印 刷 者: 北京四季青印刷厂
装 订 者: 三河市李旗庄少明装订厂
发 行 者: 新华书店总店北京发行所
开　　本: 185×230　**印张**: 23.75
版　　次: 2005 年 5 月第 1 版　2005 年 5 月第 1 次印刷
书　　号: ISBN 7-302-10720-3/TN・244
印　　数: 1～3000
定　　价: 48.00 元

出版前言

微电子技术是信息科学技术的核心技术之一，微电子产业是当代高新技术产业群的核心和维护国家主权、保障国家安全的战略性产业。我国在《信息产业“十五”计划纲要》中明确提出：坚持自主发展，增强创新能力和核心竞争力，掌握以集成电路和软件技术为重点的信息产业的核心技术，提高具有自主知识产权产品的比重。发展集成电路技术的关键之一是培养具有国际竞争力的专业人才。

微电子技术发展迅速，内容更新快，而我国微电子专业图书数量少，且内容和体系不能反映科技发展的水平，不能满足培养人才的需求，为此，我们系统挑选了一批国外经典教材和前沿著作，组织分批出版。图书选择的几个基本原则是：在本领域内广泛采用，有很大影响力；内容反映科技的最新发展，所述内容是本领域的研究热点；编写和体系与国内现有图书差别较大，能对我国微电子教育改革有所启示。本套丛书还侧重于微电子技术的实用性，选取了一批集成电路设计方面的工程技术用书，使读者能方便地应用于实践。本套丛书不仅能作为相关课程的教科书和教学参考书，也可作为工程技术人员的自学读物。

我们真诚地希望，这套丛书能对国内高校师生、工程技术人员以及科研人员的学习和工作有所帮助，对推动我国集成电路的发展有所促进。也衷心期望着广大读者对我们一如既往的关怀和支持，鼓励我们出版更多、更好的图书。

清华大学出版社

2003.9

Design of Integrated Circuits for Optical Communications

影印版序

社会信息化的进程和人们对获取信息的追求推动着信息技术和产业尤其是以光纤为网络的超高速干线数字通信系统和以无线电波为媒体的移动通信与无线接入技术和产业高速发展。可以相信，在10到20年时间内，全世界将建成以光纤通信为“中枢神经”、以其他有线和无线通信网络为“末梢神经”的庞大信息系统，实现任何人在任何地方都可以实现任何形式（语音、文字、图像）通信的理想目标。

光（纤）通信涉及光网络、光电子器件与微电子电路三大组成部分。当今，光通信系统用的微电子电路主要是以集成电路的形式实现的。因此，光通信用集成电路的研究自光纤通信发轫，一直是世界范围内研究的热点。

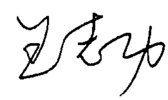
一根光纤的潜在信道容量高达几百太比特每秒（Tb/s），即 10^{14} b/s 的数量级，然而，目前构成集成电路主体元件的各类晶体管的截止频率为几十到几百吉赫兹（GHz）。由此已经构成了所谓的“电子瓶颈”。当工艺工程师通过改进工艺和开发新工艺，研制更高速晶体管来向上冲顶这一瓶颈时，电路设计工程师的任务就是应用已经开发出来的晶体管设计出尽可能高速，或称之为超高速的集成电路。在光纤通信中，超高速集成电路要处理的是频带极宽，即从0Hz开始到极高频率的超宽带数字信号。由于40Gb/s超高速数字信号频带的上限已经超过30GHz（数字信号的带宽约等于0.8倍的数据速率）进入毫米波频段，因此，加上功能电路的多样性，光通信用集成电路的设计极具挑战性。初入门者无疑渴望有这方面的教材和书籍作为参考。《光通信集成电路设计》（Design of Integrated Circuits for Optical Communications）一书正是美国加州大学洛杉矶分校（UCLA）的 Behzad Razavi 教授为研究生和实习工程师撰写的一本教材性质著作。

本书分为十章。第一章简单介绍光通信发展的历史，基本组成，设计要点和发展状况。第二章介绍随机数据的性质、生成和格式，电路有限带宽和噪声对随机数据的影响，相位抖动和传输线等基本概念。第三章讨论激光二极管，光电二极管，光纤等光器件和光系统。第四章讨论接收机中跨阻放大器的设计要点。第五章讨论限幅放大器和输出缓冲的设计技术。第六章简要讨论环行和 LC 两种振荡器和压控振荡器（VCO）以及 VCO 的数学模型等基础知识。第七章详细讨论 LC 振荡器中的电感和可变电容、LC 振荡器的差分控制和设计步骤，以及正交振荡器和分布振荡器的设计。第八章讨论简单锁相环（PLL）、电荷泵锁相环、锁相环的非线性效应、延迟锁定环路以及锁相环的应用。第九章讨论时钟和数据恢复电路（CDR）的结构、电路和噪声等问题。第十章讨论光发射机中复接电路和激光驱动器的设计。该书内容全面，理论阐述明晰，技术介绍详尽。

鉴于版权方面的原因，本影印本删去了 §6.5 约 5 页和 §7.5 约 1 页的内容，其中，§6.5 是关于 VCO 的一些数学分析，§7.5 简单介绍罕见的分布式振荡器。因此，它们的删除无损本书的完整性。

本书作者是近十多年内美国乃至世界范围内集成电路设计界一颗冉冉升起的新星。1993 至 2002 年担任号称“国际集成电路设计奥林匹克”的国际固体电路大会（ISSCC）技术程序委员会委员，IEEE 固体电路期刊，IEEE 电路与系统学报和高速电子学国际期刊的客座编辑和副编辑。获得过 1994 年 ISSCC 杰出编辑，1994 年欧洲固体电路会议和 1998 年 IEEE 专用集成电路会议最佳论文，1995 年和 1997 年 ISSCC 最佳座谈会主持人等一系列大奖。除本书之外，还发表有“Principle of Data Conversion System Design”（IEEE Press 1995），“RF Microelectronics”（Prentice Hall, 1998）和“Design of Analog CMOS Integrated Circuits”（McGraw-Hill,2001）等专著。这些著作不仅在美国，而且在世界上都产生了重要影响。

可以相信，这本专著影印本的出版发行对我国光通信集成电路设计技术的研究和产业的发展都会起到推进作用。



2004 年 11 月 14 日

于东南大学

To Angelina

About the Author

Behzad Razavi received the B.Sc. degree in electrical engineering from Sharif University of Technology in 1985 and the M.Sc. and Ph.D. degrees in electrical engineering from Stanford University in 1988 and 1992, respectively. He was with AT&T Bell Laboratories and Hewlett-Packard Laboratories until 1996. Since September 1996, he has been Associate Professor and subsequently Professor of Electrical Engineering at the University of California, Los Angeles. His current research includes wireless transceivers, frequency synthesizers, phase-locking and clock recovery for high-speed data communications, and data converters.

Professor Razavi was an Adjunct Professor at Princeton University, Princeton, NJ, from 1992 to 1994, and at Stanford University in 1995. He served on the Technical Program Committee of the International Solid-State Circuits Conference (ISSCC) from 1993 to 2002 and is presently a member of the Technical Program Committee of Symposium on VLSI Circuits. He has also served as Guest Editor and Associate Editor of the IEEE Journal of Solid-State Circuits, IEEE Transactions on Circuits and Systems, and International Journal of High Speed Electronics.

Professor Razavi received the Beatrice Winner Award for Editorial Excellence at the 1994 ISSCC, the best paper award at the 1994 European Solid-State Circuits Conference, the best panel award at the 1995 and 1997 ISSCC, the TRW Innovative Teaching Award in 1997, and the best paper award at the IEEE Custom Integrated Circuits Conference in 1998. He was the co-recipient of both the Jack Kilby Outstanding Student Paper Award and the Beatrice Winner Award for Editorial Excellence at the 2001 ISSCC. He is an IEEE Distinguished Lecturer and the author of *Principles of Data Conversion System Design* (IEEE Press, 1995), *RF Microelectronics* (Prentice Hall, 1998) (also translated to Japanese by Tadahiro Kuroda), and *Design of Analog CMOS Integrated Circuits* (McGraw-Hill, 2001), and the editor of *Monolithic Phase-Locked Loops and Clock Recovery Circuits* (IEEE Press, 1996).

Preface

The increasing demand for high-speed transport of data has revitalized optical communications, leading to extensive work on high-speed device and circuit design. This book has been written to address the need for a tutorial text dealing with the analysis and design of integrated circuits (ICs) for optical communication systems and will prove useful to both graduate students and practicing engineers. The book assumes a solid understanding of analog design, e.g., at the level of *Design of Analog CMOS Integrated Circuits* by B. Razavi or *Analysis and Design of Analog Integrated Circuits* by P. Gray, P. Hurst, S. Lewis, and R. Meyer.

The book comprises ten chapters. Chapter 1 provides an introduction to optical communications, setting the stage for subsequent developments. Chapter 2 describes basic concepts, building the foundation for analysis and design of circuits. Chapter 3 deals with optical devices and systems, bridging the gap between optics and electronics.

Chapter 4 addresses the design of transimpedance amplifiers, focusing on low-noise broadband topologies and their trade-offs. Chapter 5 extends these concepts to limiting amplifiers and output buffers, introducing methods of achieving a high gain with a broad bandwidth.

Chapter 6 presents oscillator fundamentals, and Chapter 7 focuses on LC oscillators. Chapter 8 describes the design of phase-locked loops, and Chapter 9 applies the idea of phase locking to clock and data recovery circuits. Chapter 10 deals with high-speed transmitter circuits such as multiplexers and laser drivers.

The book can be adopted for a graduate course on high-speed IC design. In a quarter system, parts of Chapters 3, 4, and 10 may be skipped. In a semester system, all chapters can be covered.

A website for the book provides additional resources for the reader, including an image set and web links. Visit www.mhhe.com/razavi for more information.

I would like to express my gratitude to the reviewers who provided invaluable feedback on all aspects of the book. Specifically, I am thankful to Lawrence Der (Transpectrum), Larry DeVito (Analog Devices), Val Garuts (TDK Semiconductor), Michael Green (University of California, Irvine), Yuriy Greshishchev (Nortel Networks), Qiuting Huang (Swiss Federal Institute of Technology), Jaime Kardontchik (TDK Semiconductor), Tai-Cheng Lee (National Taiwan University), Howard Luong (Hong Kong University of Science and Technology), Bradley Minch (Cornell University), Hakki Ozuc (TDK Semiconductor), Ken Pedrotti (University of California, Santa Cruz), Gabor Temes (Oregon State University), and Barry Thompson (TDK Semoconductor). I also wish to thank Michelle Flomenhoft, Betsy Jones, and Gloria Schiesl of McGraw-Hill for their kind support.

My wife, Angelina, encouraged me to start writing this book soon after we were married. She typed the entire text and endured my late work hours—always with a smile. I am very grateful to her.

Behzad Razavi
July 2002

Contents

CHAPTER 1

Introduction to Optical Communications

The rapidly-growing volumes of data in telecommunication networks have rekindled interest in high-speed optical and electronic devices and systems. With the proliferation of the Internet and the rise in the speed of microprocessors and memories, the transport of data continues to be the bottleneck, motivating work on faster communication channels.

The idea of using light as a carrier for signals has been around for more than a century, but it was not until the mid-1950s that researchers demonstrated the utility of the optical fiber as a medium for light propagation [1]. Even though early fibers suffered from a high loss, the prospect of guided transmission of light with a very wide modulation band ignited extensive research in the area of optical communications, leading to the practical realization of optical networks in the 1970s.

This chapter provides an overview of optical communications, helping the reader understand how the concepts introduced in subsequent chapters fit into the "big picture." We begin with a brief history and study a generic optical system, describing its principal functions. Next, we present the challenges in the design of modern optical transceivers. Finally, we review the state of the art and the trends in transceiver design.

1.1 Brief History

Attempts to "guide" light go back to the 1840s, when a French physicist named Jacque Babinet demonstrated that light could be "bent" along a jet of water. By the late 1800s, researchers had discovered that light could travel inside bent rods made of quartz. The "fiber" was thus born as a flexible, transparent rod of glass or plastic.

In 1954, Abraham van Heel of the Technical University of Delft (Holland) and Harold Hopkins and Narinder Kapany of the Imperial College (Britain) independently published the idea of using a bundle of fibers to transmit images. Around the same time, Brian O'Brien of the American Optical Company recognized that "bare" fibers lost energy to the surrounding air, motivating van Heel to enclose the fiber core in a coating and hence lower the loss. Fiber loss was still very high, about 1,000 dB/km, limiting the usage to endoscopy applications.

The introduction of the laser as an intense light source in the 1950s and 1960s played a crucial role in fiber optics. The broadband modulation capability of lasers offered great potential for carrying information, although no suitable propagation medium seemed available. In 1966, Charles Ko and Charles Hockem of the Standard Telecommunication Laboratory (Britain) proposed that the optical fiber could be utilized as a signal transmission medium if the loss was lowered to 20 dB/km. They also postulated that such a low loss would be obtained if the impurities in the fiber material were reduced substantially.

Four years later, Robert Mauer and two of his colleagues at Corning Glass Works demonstrated silica fibers having a loss of less than 20 dB/km. With advances in semiconductor industry, the art of reducing impurities and dislocations in fibers improved as well, leading to a loss of 4 dB/km in 1975 and 0.2 dB/km in 1979. The dream of carrying massive volumes of information over long distances was thus fulfilled: in 1977, AT&T and GTE deployed the first fiber optic telephone system.

The widespread usage of optical communication for the transport of high-speed data stems from (1) the large bandwidth of fibers (roughly 25 to 50 GHz) and (2) the low loss of fibers (0.15 to 0.2 dB/km). By comparison, the loss reaches 200 dB/km at 100 MHz for twisted-pair cables and 500 dB/km at 1 GHz for low-cost coaxial cables. Also, wireless propagation with carrier frequencies of several gigahertz incurs an attenuation of tens of decibels across a few meters while supporting data rates lower than 100 Mb/s.

The large (and free) bandwidth provided by fibers has led to another important development: the use of multiple wavelengths (frequencies) to carry several channels on a single fiber. For example, it has been demonstrated that 100 wavelengths, each carrying data at 10 Gb/s, allow communication at an overall rate of 1 Tb/s across 400 km.

1.2 Generic Optical System

The goal of an optical communication (OC) system is to carry large volumes of data across a long distance. For example, the telephone traffic in Europe is connected to that in the United States through a fiber system installed across the Atlantic Ocean.

Depicted in Fig. 1.1(a), a simple OC system consists of three components: (1) an electro-optical transducer (e.g., a laser diode), which converts the electrical data to optical form (i.e., it produces light for logical ONEs and remains off for logical ZEROs); (2) a fiber, which carries the light produced by the laser; and (3) a photodetector (e.g., a photodiode), which senses the light at the end of the fiber and converts it to an electrical signal. We call the transmit and receive sides the "near end" and the "far end," respectively. As explained in Chapter 3, lasers are driven by electrical currents, and photodiodes generate an output current.

With long or low-cost fibers, the light experiences considerable attenuation as it travels from the near end to the far end. Thus, (1) the laser must produce a high light intensity, e.g., tens of milliwatts; (2) the photodiode must exhibit a high sensitivity to light; and (3) the electrical signal generated by the photodiode must be amplified with low noise. These observations lead to the more complete system shown in Fig. 1.1(b), where a "laser driver" delivers large currents to the laser and a "transimpedance amplifier" (TIA) amplifies the photodiode output with low noise and sufficient bandwidth, converting it to a voltage. For

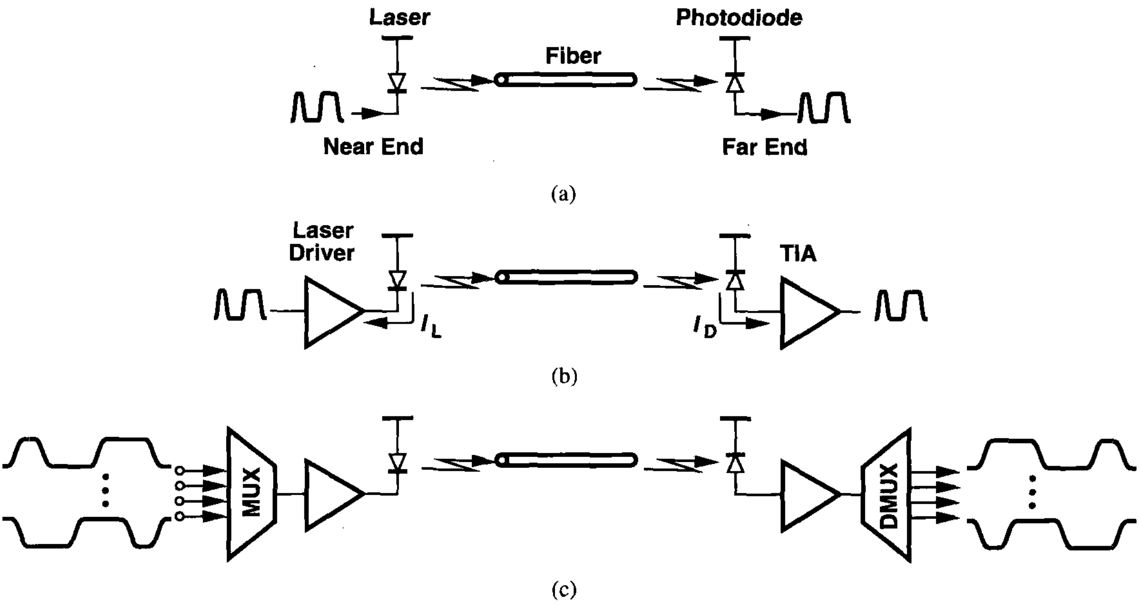


Figure 1.1 (a) Simple optical system, (b) addition of driver and amplifier, (c) addition of MUX and DMUX.

example, data at a rate of 10 Gb/s may be applied to the laser driver, modulate the laser light at a wavelength of 1.55 μm, and emerge at the output of the TIA with an amplitude of 10 mV.

The transmit and receive operations in Fig. 1.1(b) process high-speed "serial" data, e.g., a single stream of data at 10 Gb/s. However, the actual data provided to the transmitter (TX) is in the form of many low-speed channels ("parallel" data) because it is generated by multiple users. The task of parallel-to-serial conversion is performed by a "multiplexer" (MUX). Similarly, the receiver (RX) must incorporate a "demultiplexer" (DMUX) to reproduce the original parallel channels. The resulting system is shown in Fig. 1.1(c).

The topology of Fig. 1.1(c) is still incomplete. Let us first consider the transmit end. The multiplexer requires a number of clock frequencies with precise edge alignment. These clocks are generated by a phase-locked loop (PLL). Furthermore, in practice, the MUX output suffers from nonidealities such as "jitter" and "intersymbol interference" (ISI), mandating the use of a "clean-up" flipflop before the laser driver. These modifications lead to the transmitter illustrated in Fig. 1.2(a).

The receive end also requires additional functions. Since the TIA output swing may not be large enough to provide logical levels, a high-gain amplifier (called a "limiting amplifier") must follow the TIA. Moreover, since the received data may exhibit substantial noise, a clean-up flipflop (called a "decision circuit") is interposed between the limiting amplifier and the DMUX. The receiver thus appears as shown in Fig. 1.2(b).

The receiver of Fig. 1.2(b) lacks a means of generating the clock necessary for the de-