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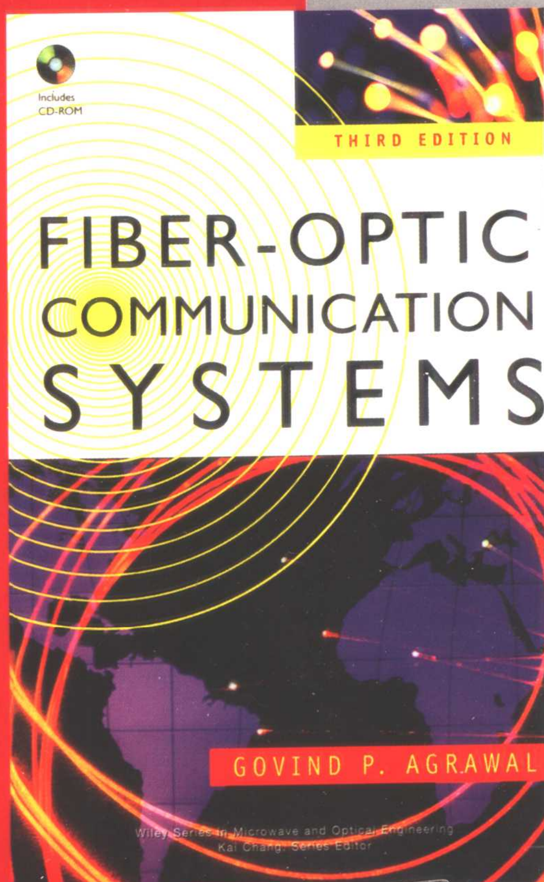
国外大学优秀教材 —— 通信系列（影印版）

Govind P. Agrawal

光纤通信系统

（第3版）



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Fiber-Optic Communication Systems

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影 印 版 序

自从 1970 年低损耗的石英光纤和在室温下连续工作的半导体激光器取得突破性进展以来，光纤通信技术进入了一个迅猛发展的阶段。近 30 年来，光纤通信系统从 1975 年的速率为 45Mb/s、传输距离为 10km 左右发展到如今单纤中最高累计速率为 10.92Tb/s、最长实验传输距离达到近 3 万 km，系统的速率与传输距离的乘积（BL）一直以每年翻一番的趋势增长，增长速度超过了著名的摩尔定律。光纤系统性能的巨大进展极大地提高了全球通信网络的容量和覆盖范围，在“信息高速公路”的建设乃至全球信息化的进程中发挥了关键的作用。因此，目前国内外许多大学的电子工程、物理和光学等领域的有关专业中都开设光纤通信课程，相应的教材、参考书和专著已不胜枚举。美国罗彻斯特大学的 Govind P. Agrawal 教授的《光纤通信系统》一书在国内外享有盛誉。本书于 1992 年问世，10 多年来一直受到光通信界的认可，许多大学将它作为教材或参考书。本书再版于 1997 年。由于近年来光纤通信技术的快速发展，作者又于 2002 年推出了目前的第三版。其主要目标依然与前两版一样，即一方面能够作为教科书使用，同时又能供光通信界科技工作者作参考。因此，物理的理解是本书的重点，但工程方面内容的讨论也贯穿各章的始终。

概括起来，本书有如下特点：

（1）内容系统全面。本书从最基本的光纤、光发射和光接收机讲起，随后按章节分别讨论了系统设计、光纤损耗和色散管理所涉及的先进技术、光网络中的波分复用、时分复用及码分复用技术。光孤子，以及相干光通信系统等。书中内容反映了到 2001 年为止光纤通信系统最新和全面的状况。

（2）注重概念方法。从内容的整体编排到具体内容的叙述，都体现了突出物理概念、强调基本分析方法的指导思想。为了便于读者理解概念，本书采用了大量清晰的插图和内容详实的表格。

（3）例题习题丰富。书中有大量的例题和习题。书后并附有一张由 Optiwave 公司提供的 CD 光盘，其中包含了一个光纤通信系统设计用的软件包。光盘中有大量的例题，读者能够利用这些例题了解该软件包的各种功能，然后可使用该软件包求解本书各章结尾部分提供的习题，这将有助于读者加深对光通信系统设计中重要难点的理解。

本书的作者从 1989 年起在美国罗彻斯特大学光学院讲授光纤通信系统课程，

且与工业界合作密切，因此本书的内容不仅适合教学，而且反映了工业界的最新发展。本书的主要用途是作为光通信专业研究生的教材，内容经适当筛选后也能用于高年级的本科生。书中的主干内容与国内教材基本一致，因此很适合作为国内光纤通信和光电子技术应用等相关课程的教学参考书。在当前高校中正大力推进采用外语讲学的形势下，本书更是英文版教材中一个较好的选择。

谢世钟教授
清华大学电子工程系光通信研究所
2004 年 5 月

Preface

Since the publication of the first edition of this book in 1992, the state of the art of fiber-optic communication systems has advanced dramatically despite the relatively short period of only 10 years between the first and third editions. For example, the highest capacity of commercial fiber-optic links available in 1992 was only 2.5 Gb/s. A mere 4 years later, the wavelength-division-multiplexed (WDM) systems with the total capacity of 40 Gb/s became available commercially. By 2001, the capacity of commercial WDM systems exceeded 1.6 Tb/s, and the prospect of lightwave systems operating at 3.2 Tb/s or more were in sight. During the last 2 years, the capacity of transoceanic lightwave systems installed worldwide has exploded. Moreover, several other undersea networks were in the construction phase in December 2001. A global network covering 250,000 km with a capacity of 2.56 Tb/s (64 WDM channels at 10 Gb/s over 4 fiber pairs) is scheduled to be operational in 2002. Several conference papers presented in 2001 have demonstrated that lightwave systems operating at a bit rate of more than 10 Tb/s are within reach. Just a few years ago it was unimaginable that lightwave systems would approach the capacity of even 1 Tb/s by 2001.

The second edition of this book appeared in 1997. It has been well received by the scientific community involved with lightwave technology. Because of the rapid advances that have occurred over the last 5 years, the publisher and I deemed it necessary to bring out the third edition if the book were to continue to provide a comprehensive and up-to-date account of fiber-optic communication systems. The result is in your hands. The primary objective of the book remains the same. Specifically, it should be able to serve both as a textbook and a reference monograph. For this reason, the emphasis is on the physical understanding, but the engineering aspects are also discussed throughout the text.

Because of the large amount of material that needed to be added to provide comprehensive coverage, the book size has increased considerably compared with the first edition. Although all chapters have been updated, the major changes have occurred in Chapters 6–9. I have taken this opportunity to rearrange the material such that it is better suited for a two-semester course on optical communications. Chapters 1–5 provide the basic foundation while Chapters 6–10 cover the issues related to the design of advanced lightwave systems. More specifically, after the introduction of the elementary concepts in Chapter 1, Chapters 2–4 are devoted to the three primary components of a fiber-optic communications—optical fibers, optical transmitters, and optical receivers. Chapter 5 then focuses on the system design issues. Chapters 6 and 7 are devoted to the advanced techniques used for the management of fiber losses and chromatic dispersion, respectively. Chapter 8 focuses on the use of wavelength- and time-division multiplexing techniques for optical networks. Code-division multiplexing is also a part of this chapter. The use of optical solitons for fiber-optic systems is discussed in Chapter 9. Coherent lightwave systems are now covered in the last chapter. More than 30% of the material in Chapter 6–9 is new because of the rapid development of the WDM technology over the last 5 years. The contents of the book reflect the state of the art of lightwave transmission systems in 2001.

The primary role of this book is as a graduate-level textbook in the field of *optical communications*. An attempt is made to include as much recent material as possible so that students are exposed to the recent advances in this exciting field. The book can also serve as a reference text for researchers already engaged in or wishing to enter the field of optical fiber communications. The reference list at the end of each chapter is more elaborate than what 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. A set of problems is included at the end of each chapter to help both the teacher and the student. Although written primarily for graduate students, the book can also be used for an undergraduate course at the senior level with an appropriate selection of topics. Parts of the book can be used for several other related courses. For example, Chapter 2 can be used for a course on optical waveguides, and Chapter 3 can be useful for a course on optoelectronics.

Many universities in the United States and elsewhere offer a course on optical communications as a part of their curriculum in electrical engineering, physics, or optics. I have taught such a course since 1989 to the graduate students of the Institute of Optics, and this book indeed grew out of my lecture notes. I am aware that it is used as a textbook by many instructors worldwide—a fact that gives me immense satisfaction. I am acutely aware of a problem that is a side effect of an enlarged revised edition. How can a teacher fit all this material in a one-semester course on *optical communications*? I have to struggle with the same question. In fact, it is impossible to cover the entire book in one semester. The best solution is to offer a two-semester course covering Chapters 1 through 5 during the first semester, leaving the remainder for the second semester. However, not many universities may have the luxury of offering a two-semester course on optical communications. The book can be used for a one-semester course provided that the instructor makes a selection of topics. For example, Chapter 3 can be skipped if the students have taken a laser course previously. If only parts of Chapters 6 through 10 are covered to provide students a glimpse of the recent advances, the material can fit in a single one-semester course offered either at the senior level for undergraduates or to graduate students.

This edition of the book features a compact disk (CD) on the back cover provided by the Optiwave Corporation. The CD contains a state-of-the art software package suitable for designing modern lightwave systems. It also contains additional problems for each chapter that can be solved by using the software package. Appendix E provides more details about the software and the problems. It is my hope that the CD will help to train the students and will prepare them better for an industrial job.

A large number of persons have contributed to this book either directly or indirectly. It is impossible to mention all of them by name. I thank my graduate students and the students who took my course on optical communication systems and helped improve my class notes through their questions and comments. Thanks are due to many instructors who not only have adopted this book as a textbook for their courses but have also pointed out the misprints in previous editions, and thus have helped me in improving the book. I am grateful to my colleagues at the Institute of Optics for numerous discussions and for providing a cordial and productive atmosphere. I appreciated the help of Karen Rolfe, who typed the first edition of this book and made numerous revisions with a smile. Last, but not least, I thank my wife, Anne, and my daughters, Sipra, Caroline, and Claire, for understanding why I needed to spend many weekends on the book instead of spending time with them.

Govind P. Agrawal

Rochester, NY
December 2001

Contents

Chapter 1

Introduction

A communication system transmits information from one place to another, whether separated by a few kilometers or by transoceanic distances. Information is often carried by an electromagnetic carrier wave whose frequency can vary from a few megahertz to several hundred terahertz. Optical communication systems use high carrier frequencies (~ 100 THz) in the visible or near-infrared region of the electromagnetic spectrum. They are sometimes called lightwave systems to distinguish them from microwave systems, whose carrier frequency is typically smaller by five orders of magnitude (~ 1 GHz). Fiber-optic communication systems are lightwave systems that employ optical fibers for information transmission. Such systems have been deployed worldwide since 1980 and have indeed revolutionized the technology behind telecommunications. Indeed, the lightwave technology, together with microelectronics, is believed to be a major factor in the advent of the "information age." The objective of this book is to describe fiber-optic communication systems in a comprehensive manner. The emphasis is on the fundamental aspects, but the engineering issues are also discussed. The purpose of this introductory chapter is to present the basic concepts and to provide the background material. Section 1.1 gives a historical perspective on the development of optical communication systems. In Section 1.2 we cover concepts such as analog and digital signals, channel multiplexing, and modulation formats. Relative merits of guided and unguided optical communication systems are discussed in Section 1.3. The last section focuses on the building blocks of a fiber-optic communication system.

1.1 Historical Perspective

The use of light for communication purposes dates back to antiquity if we interpret optical communications in a broad sense [1]. Most civilizations have used mirrors, fire beacons, or smoke signals to convey a single piece of information (such as victory in a war). Essentially the same idea was used up to the end of the eighteenth century through signaling lamps, flags, and other semaphore devices. The idea was extended further, following a suggestion of Claude Chappe in 1792, to transmit mechanically