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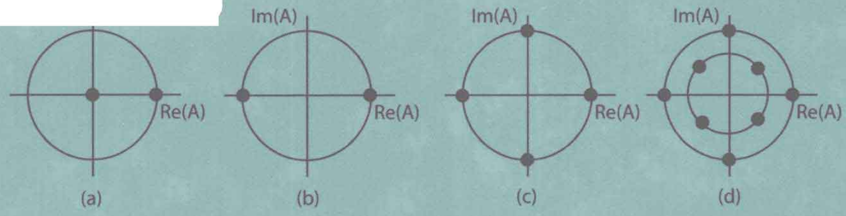
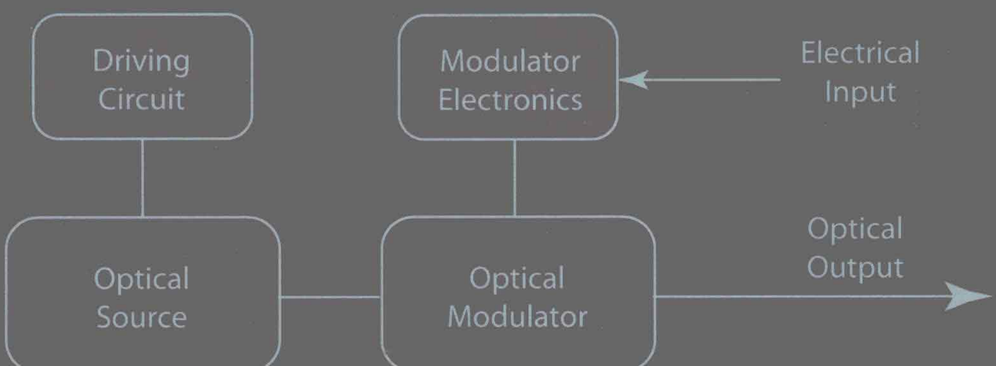


FIBER–OPTIC COMMUNICATION SYSTEMS

FOURTH EDITION

GOVIND P. AGRAWAL



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FIBER-OPTIC COMMUNICATION SYSTEMS

Fourth Edition

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Rochester, New York

WILEY

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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 18 years between the first and fourth editions. The highest capacity of commercial fiber-optic links available in 1992 was only 2.5 Gb/s. A mere 4 years later, with the advent of wavelength-division multiplexing (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. At the same time, the capacity of transoceanic lightwave systems installed worldwide exploded. 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) was planned in 2001 and became operational by 2004 (currently operated by VSNL, an Indian telecommunication company). Although the pace slowed down after 2001 for a few years with the bursting of the so-called "telecom bubble," progress in the design of lightwave systems continued and accelerated after 2006 with the advent of phase-based modulation formats, 100-Gb Ethernet, and orthogonal frequency-division multiplexing.

The third edition of this book appeared in 2002. It has been well received by the scientific community involved with lightwave technology as well as by the educational community, judging from book's adoption as a textbook for courses offered at many universities worldwide. Because of the rapid advances that have occurred over the last 8 years, the publisher and I deemed it necessary to bring out the fourth 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 7–11. I have taken this opportunity to rearrange the material such that it is better suited for a two-semester course on optical communications. In particular, the chapter on WDM systems has been moved earlier and now appears as Chapter 6. With this arrangement, Chapters 1 to 6 provide the basic foundation, while Chapters 7 to 11 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. Chapters 5 and 6 then focus on the design issues relevant for single-channel and multichannel systems, respectively. Chapters 7 and 8 are devoted to the advanced techniques used for the management of fiber losses and chromatic dispersion, respectively. Chapter 9 focuses on the impact of nonlinear effects and techniques used to manage them such as the use of optical solitons and pseudo-linear propagation through enhanced dispersion. Chapters 10 and 11 are new to the fourth edition. Chapter 10 focuses primarily on the coherent and self-coherent lightwave systems making use of the novel phase-based modulation formats. Chapter 11 is devoted to all-optical signal processing with emphasis on wavelength conversion and optical regeneration. The contents of the book reflect the state of the art of lightwave systems in 2010.

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 Chapters 3 and 4 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 6 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 7 through 11 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.

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 D 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
April 2010

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 ($\sim$100 THz) in the visible or near-infrared region of the electromagnetic spectrum. They are sometimes called lightwave systems to distinguish them from microwave systems, whose carrier frequency is typically smaller by five orders of magnitude ($\sim$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 revolutionized the field of telecommunications. Indeed, lightwave technology, together with microelectronics, led to the advent of the "information age" during the 1990s. This book describes fiber-optic communication systems in a comprehensive manner. The emphasis is on the fundamental aspects, but relevant engineering issues are also discussed. In this introductory chapter we present the basic concepts and provide the background material. Section 1.1 gives a historical perspective on the development of optical communication systems. Section 1.2 covers concepts such as analog and digital signals, channel multiplexing, and modulation formats. Relative merits of various lightwave 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 coded messages over long distances ($\sim$100 km) by the use of intermediate relay stations [2], acting as *regenerators* or *repeaters* in the modern-day language. Figure 1.1

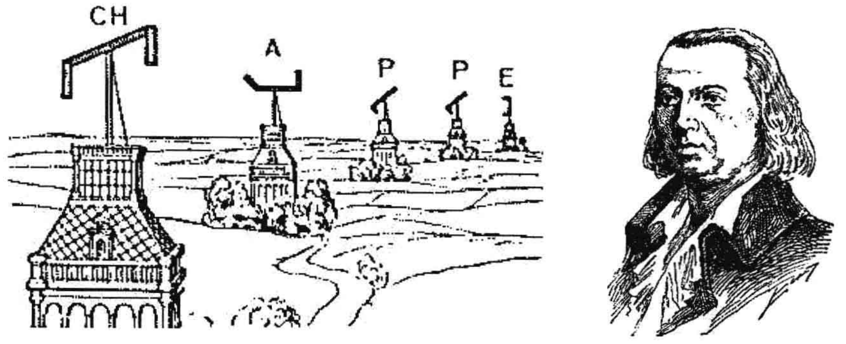

Figure 1.1: Schematic illustration of the optical telegraph and its inventor Claude Chappe. (After Ref. [2]; ©1944 American Association for the Advancement of Science; reprinted with permission.)

shows the basic idea schematically. The first such "optical telegraph" was put in service between Paris and Lille (two French cities about 200 km apart) in July 1794. By 1830, the network had expanded throughout Europe [1]. The role of light in such systems was simply to make the coded signals visible so that they could be intercepted by the relay stations. The opto-mechanical communication systems of the nineteenth century were inherently slow. In modern-day terminology, the effective bit rate of such systems was less than 1 bit per second ($B < 1$ b/s).

1.1.1 Need for Fiber-Optic Communications

The advent of telegraphy in the 1830s replaced the use of light by electricity and began the era of electrical communications [3]. The bit rate B could be increased to ~ 10 b/s by the use of new coding techniques, such as the *Morse code*. The use of intermediate relay stations allowed communication over long distances (~ 1000 km). Indeed, the first successful transatlantic telegraph cable went into operation in 1866. Telegraphy used essentially a digital scheme through two electrical pulses of different durations (dots and dashes of the Morse code). The invention of the telephone in 1876 brought a major change inasmuch as electric signals were transmitted in analog form through a continuously varying electric current [4]. Analog electrical techniques were to dominate communication systems for a century or so.

The development of worldwide telephone networks during the twentieth century led to many advances in the design of electrical communication systems. The use of coaxial cables in place of wire pairs increased system capacity considerably. The first coaxial-cable system, put into service in 1940, was a 3-MHz system capable of transmitting 300 voice channels or a single television channel. The bandwidth of such systems is limited by the frequency-dependent cable losses, which increase rapidly for frequencies beyond 10 MHz. This limitation led to the development of microwave communication systems in which an electromagnetic carrier wave with frequencies in the range of 1–10 GHz is used to transmit the signal by using suitable modulation techniques.

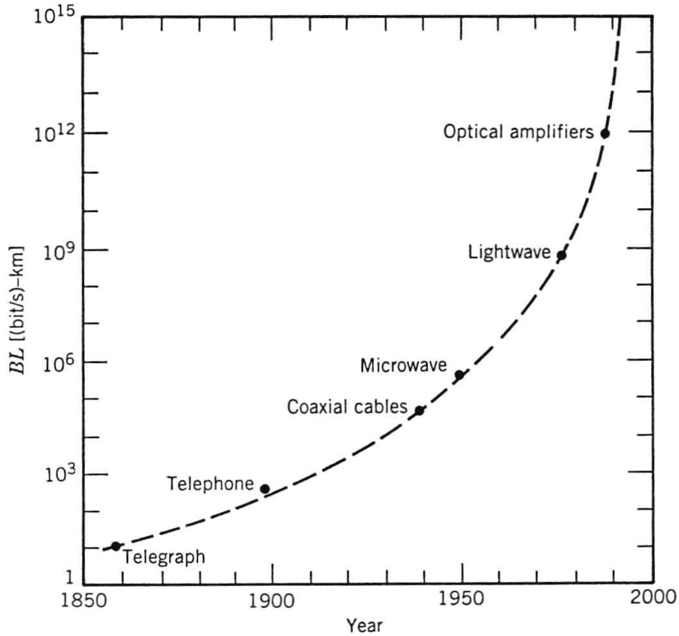

Figure 1.2: Increase in bit rate–distance product *BL* during the period 1850–2000. The emergence of a new technology is marked by a solid circle.

The first microwave system operating at the carrier frequency of 4 GHz was put into service in 1948. Since then, both coaxial and microwave systems have evolved considerably and are able to operate at bit rates $\sim$100 Mb/s. The most advanced coaxial system was put into service in 1975 and operated at a bit rate of 274 Mb/s. A severe drawback of such high-speed coaxial systems is their small *repeater spacing* ($\sim$1 km), which makes the system relatively expensive to operate. Microwave communication systems generally allow for a larger repeater spacing, but their bit rate is also limited by the carrier frequency of such waves. A commonly used figure of merit for communication systems is the *bit rate–distance product*, *BL*, where *B* is the bit rate and *L* is the repeater spacing. Figure 1.2 shows how the *BL* product has increased through technological advances during the last century and a half. Communication systems with $BL \sim 100$ (Mb/s)-km were available by 1970 and were limited to such values because of fundamental limitations.

It was realized during the second half of the twentieth century that an increase of several orders of magnitude in the *BL* product would be possible if optical waves were used as the carrier. However, neither a coherent optical source nor a suitable transmission medium was available during the 1950s. The invention of the laser and its demonstration in 1960 solved the first problem [5]. Attention was then focused on finding ways for using laser light for optical communications. Many ideas were advanced during the 1960s [6], the most noteworthy being the idea of light confinement using a sequence of gas lenses [7].