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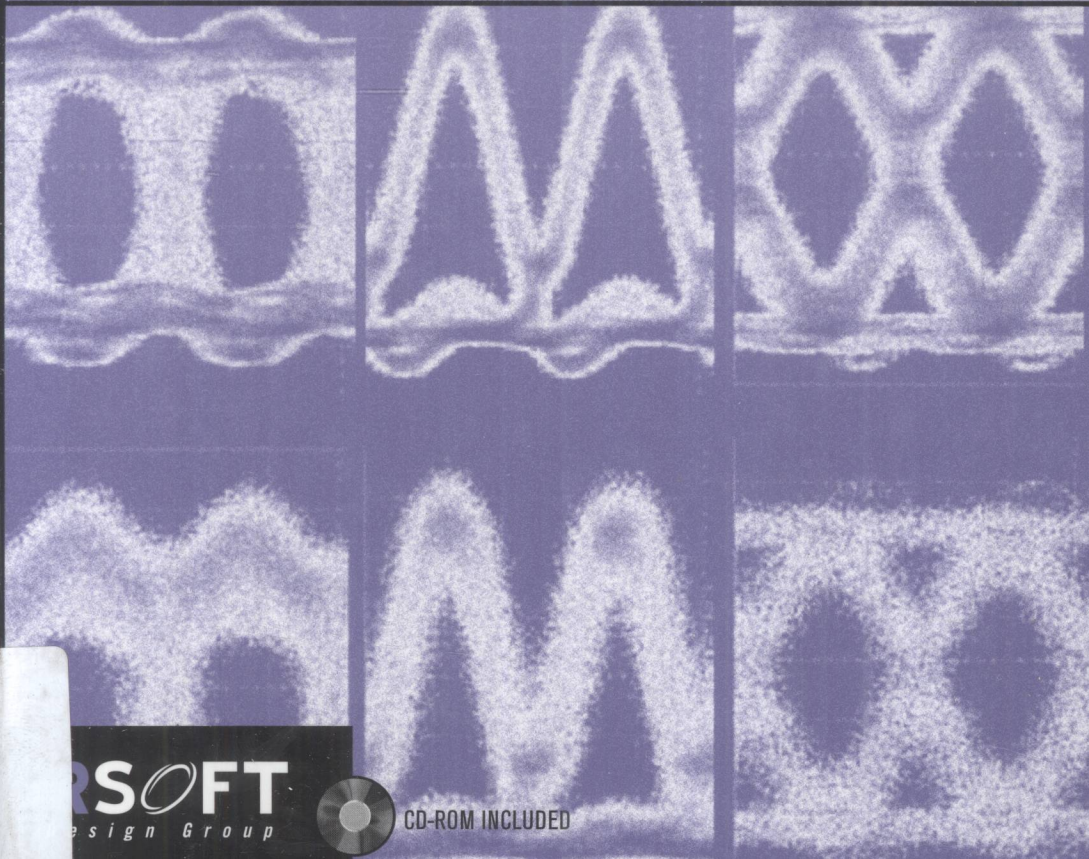
Lightwave Technology

Telecommunication Systems

Govind P. Agrawal



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LIGHTWAVE TECHNOLOGY

Telecommunication Systems

Govind P. Agrawal

The Institute of Optics
University of Rochester
Rochester, NY

WILEY-INTERSCIENCE

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LIGHTWAVE TECHNOLOGY

For Anne, Sipra, Caroline, and Claire

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Preface

The term *lightwave technology* was coined as a natural extension of microwave technology and refers to the developments based on the use of light in place of microwaves. The beginnings of lightwave technology can be traced to the decade of 1960s during which significant advances were made in the fields of lasers, optical fibers, and nonlinear optics. The two important milestones were realized in 1970, the year that saw the advent of low-loss optical fibers as well as the room-temperature operation of semiconductor lasers. By 1980, the era of commercial lightwave transmission systems has arrived.

The first generation of fiber-optic communication systems debuting in 1980 operated at a meager bit rate of 45 Mb/s and required signal regeneration every 10 km or so. However, by 1990 further advances in lightwave technology not only increased the bit rate to 10 Gb/s (by a factor of 200) but also allowed signal regeneration after 80 km or more. The pace of innovation in all fields of lightwave technology only quickened during the 1990s, as evident from the development and commercialization of erbium-doped fiber amplifiers, fiber Bragg gratings, and wavelength-division-multiplexed lightwave systems. By 2001, the capacity of commercial terrestrial systems exceeded 1.6 Tb/s. At the same time, the capacity of transoceanic lightwave systems installed worldwide exploded. A single transpacific system could transmit information at a bit rate of more than 1 Tb/s over a distance of 10,000 km without any signal regeneration. Such a tremendous improvement was possible only because of multiple advances in all areas of lightwave technology. Although commercial development slowed down during the economic downturn that began in 2001, it was showing some signs of recovery by the end of 2004, and lightwave technology itself has continued to grow.

The primary objective of this two-volume book is to provide a comprehensive and up-to-date account of all major aspects of lightwave technology. The first volume, subtitled *Components and Devices*, is devoted to a multitude of silica- and semiconductor-based optical devices. The second volume, subtitled *Telecommunication Systems*, deals with the design of modern lightwave systems; the acronym LT1 is used to refer to the material in the first volume. The first two introductory chapters cover topics such as modulation formats and multiplexing techniques employed to form an optical bit stream. Chapters 3 through 5 consider the degradation of such an optical signal through loss, dispersion, and nonlinear effects during its transmission through optical fibers and how they affect the system performance. Chapters 6 through 8 focus on the management of the degradation caused by noise, dispersion, and fiber nonlinearity. Chapters 9

and 10 cover the engineering issues related to the design of WDM systems and optical networks.

This text is intended to serve both as a textbook and a reference monograph. For this reason, the emphasis is on physical understanding, but engineering aspects are also discussed throughout the text. Each chapter also includes selected problems that can be assigned to students. The book's primary readership is likely to be graduate students, research scientists, and professional engineers working in fields related to lightwave technology. 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 reference section at the end of each chapter is more extensive than what is common for a typical textbook. The listing of recent research papers should be helpful to researchers using this book as a reference. At the same time, students can benefit from this feature if they are assigned problems requiring reading of the original research papers. This book may be useful in an upper-level graduate course devoted to optical communications. It can also be used in a two-semester course on optoelectronics or lightwave technology.

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. I am grateful to my colleagues at the Institute of Optics for numerous discussions and for providing a cordial and productive atmosphere. I thank, in particular, René Essiambre and Qiang Lin for reading several chapters and providing constructive feedback. Last, but not least, I thank my wife Anne and my daughters, Sipra, Caroline, and Claire, for their patience and encouragement.

Govind P. Agrawal

Rochester, NY
December 2004

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Chapter 1

Introduction

Lightwave systems represent a natural extension of microwave communication systems inasmuch as information is transmitted over an electromagnetic carrier in both types of systems. The major difference from a conceptual standpoint is that, whereas carrier frequency is typically $\sim$1 GHz for microwave systems, it increases by five orders of magnitude and is typically $\sim$100 THz in the case of lightwave systems. This increase in carrier frequency translates into a corresponding increase in the system capacity. Indeed, whereas microwave systems rarely operate above 0.2 Gb/s, commercial lightwave systems can operate at bit rates exceeding 1 Tb/s. Although the optical carrier is transmitted in free space for some applications related to satellites and space research, terrestrial lightwave systems often employ optical fibers for information transmission. Such fiber-optic communication systems have been deployed worldwide since 1980 and constitute the backbone behind the Internet. One can even claim that the lightwave technology together with advances in microelectronics was responsible for the advent of the "information age" by the end of the twentieth century. The objective of this book is to describe the physics and engineering behind various kinds of lightwave systems. The purpose of this introductory chapter is to present the basic concepts together with the background material. Section 1.1 provides a historical perspective on the development of lightwave communication systems. Section 1.2 focuses on the building blocks of such a system and describes briefly the three components known as optical transmitters, fibers, and receivers. Section 1.3 covers the concepts such as analog and digital signals and the technique used to convert between the two. Channel multiplexing in the time and frequency domains is described in Section 1.4 where we also discuss the technique of code-division multiplexing.

1.1 Evolution of Lightwave Systems

Microwave communication systems were commercialized during the decade of 1940s, and carrier frequencies of up to 4 GHz were used by 1947 for a commercial system operating between New York and Boston [1]. During the next 25 years or so, microwave as well as coaxial systems evolved considerably. Although such systems were able to

operate at bit rates of up to 200 Mb/s or so, they were approaching the fundamental limits of the technology behind them. It was realized in the 1950s that an increase of several orders of magnitude in the system capacity should be possible if optical waves were used in place of microwaves as the carrier of information. However, neither a coherent optical source, nor a suitable transmission medium, was available during the 1950s. The invention of the laser solved the first problem [2]. Attention was then focused on finding ways of transmitting laser light over long distances. In contrast with the microwaves, optical beams suffer from many problems when they are transmitted through the atmosphere. Many ideas were advanced during the 1960s to solve these problems [3], the most noteworthy being the idea of light confinement using a sequence of gas lenses [4].

In a parallel but unrelated development, optical glass fibers were developed during the 1950s, mainly from the standpoint of medical applications [5]–[9]. It was suggested in 1966 that optical fibers might be the best choice for transporting optical signals in lightwave systems [10] as they are capable of guiding the light in a manner similar to the guiding of electrons in copper wires. The main problem was their high losses since fibers available during the 1960s had losses in excess of 1,000 dB/km.

A breakthrough occurred in 1970 when fiber losses were reduced to below 20 dB/km in the wavelength region near 1 μm using a novel fabrication technique [11]. At about the same time, GaAs semiconductor lasers, operating continuously at room temperature, were demonstrated [12]. The simultaneous availability of *compact* optical sources and *low-loss* optical fibers led to a worldwide effort for developing fiber-optic communication systems during the 1970s [13]. After a successful Chicago field trial in 1977, terrestrial lightwave systems became available commercially beginning in 1980 [14]–[16]. Figure 1.1 shows the increase in the capacity of lightwave systems realized after 1980 through several generations of development. As seen there, the commer-

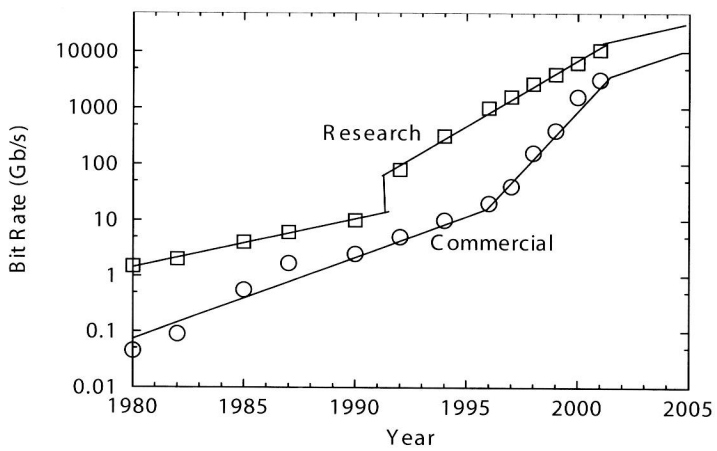

Figure 1.1: Increase in the capacity of lightwave systems realized after 1980. Commercial systems (circles) follow research demonstrations (squares) with a few-year lag. The change in the slope after 1992 is due to the advent of WDM technology.

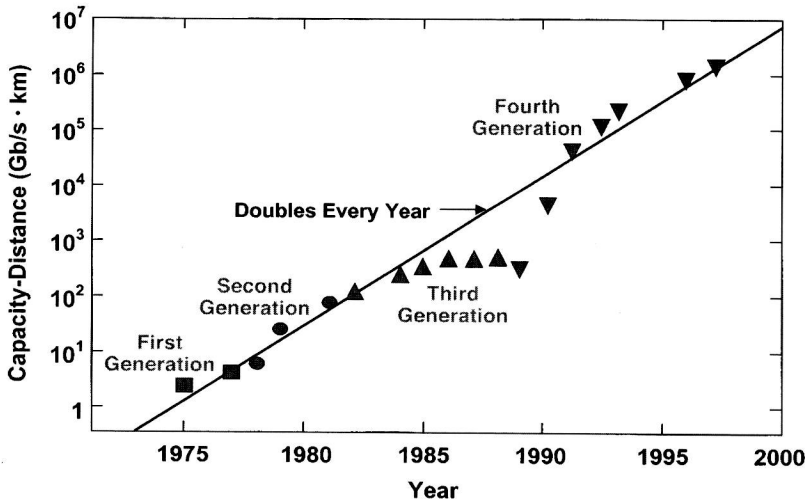

Figure 1.2: Increase in the *BL* product from 1975 to 2000 through four generations of lightwave systems. Different symbols are used for successive generations. (After Ref. [17]; ©2000 IEEE.)

cial deployment of lightwave systems followed the research and development phase closely. The progress has indeed been rapid as evident from an increase in the system capacity by a factor of 100,000 over a period of less than 25 years. The saturation of the capacity after 2000 is partly due to the economic slowdown experienced by the lightwave industry (known popularly as the bursting of the telecom bubble).

The distance over which a lightwave system can transmit data without introducing errors is also important while judging the system performance. Since signal is degraded during transmission, most lightwave systems require periodic regeneration of the optical signal through devices known as "repeaters." A commonly used figure of merit for any communication system is the *bit rate–distance product*, *BL*, where *B* is the bit rate and *L* is the repeater spacing. The research phase of lightwave systems started around 1975. The first-generation systems operated in the near infrared at a wavelength close to 800 nm and used GaAs semiconductor lasers as an optical source. They were able to work at a bit rate of 45 Mb/s and allowed repeater spacings of up to 10 km. The 10-km value may seem too small from a modern perspective, but it was 10 times larger than the 1-km spacing prevalent at that time in coaxial systems.

The enormous progress realized over the 25-year period extending from 1975 to 2000 can be grouped into four distinct generations. Figure 1.2 shows the increase in the *BL* product over this time period as quantified through various laboratory experiments [17]. The straight line corresponds to a doubling of the *BL* product every year. In every generation, *BL* increases initially but then saturates as the technology matures. Each new generation brings a fundamental change that helps to improve the system performance further.

It was clear during the 1970s that the repeater spacing could be increased considerably by operating the lightwave system in the wavelength region near 1.3 μm, where

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