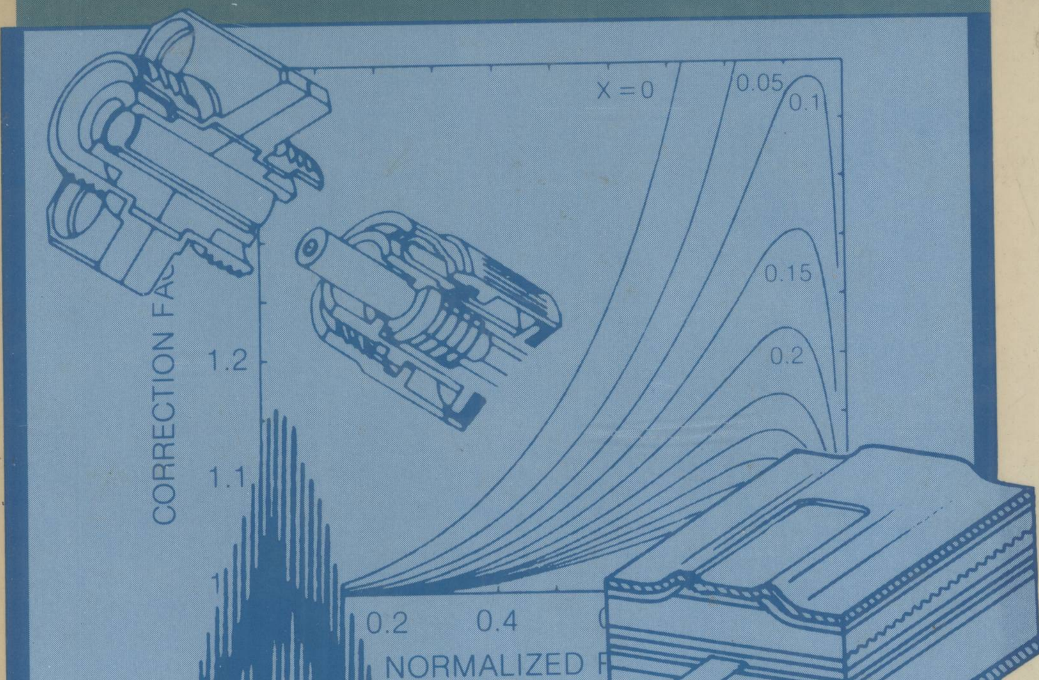
FIBER OPTICS

Devices and Systems



PETER K. CHEO

PRENTICE-HALL SERIES IN SOLID STATE PHYSICAL ELECTRONICS
Nick Holonyak, Jr., Series Editor

FIBER OPTICS
Devices and Systems

Peter K. Cheo

United Technologies Research Center
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PRENTICE-HALL SERIES IN SOLID STATE PHYSICAL ELECTRONICS

Nick Holonyak, Jr., Editor

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Dedicated
to Dorothy and my children

Preface

This book comprises an accumulation of three years of lecture notes that I prepared for a course offered at the Hartford Graduate Center to a group of first-year graduate students who are employed by aerospace, electronics, and telecommunications industries. One of the problems that confronted me was to find an appropriate textbook that would satisfy the needs of my students, most of whom obtained their bachelor degrees in electrical engineering or applied sciences several years ago and needed an extensive review of the fundamentals. There are many excellent reference books on fiber optics and on topics related to this field, but they are not suitable for use as a text. The emerging field of fiber optics actually involves several independent technologies, such as guided-wave optics, semiconductor light sources and photodetectors, and digital communications. There are excellent books available that contain detailed treatments of each of these topics. However, an introductory textbook that covers the entire field is lacking at present. On the other hand, many books provide a broad coverage of this field by offering a collection of papers in which the fundamentals are often left to references. In these cases, various aspects of fiber optics are presented by experts, each with a different writing style and approach. The lack of coherence and fundamental concepts make these books difficult for students to comprehend unless they have already acquired sufficient background knowledge and expertise in the field.

The goal of this book is to present the above-mentioned topics in a self-consistent manner so that students can follow the development of this text with a clear understanding of the subject matter. The presentation has been kept at an introductory level, with emphasis on the physical concepts underlying the interpretation of the properties of fiber optical waveguides, semiconductor light emission, and detection devices. I have made an effort to remain as rigorous and up to date as possible within the constraint of the presentation level.

This book is intended as a text for a course to be taught at the first-year graduate level to students enrolled in departments of electrical engineering, physics, and applied sciences. In this book I have treated in a pedagogic manner topics that form the basics for all optical fiber systems. The fundamental principles and theories are introduced and developed to the extent that the student can gain a better insight into each topic without losing track of the basic concepts. When mathematics becomes cumbersome, approximate methods or intuitive approaches are introduced to provide students with a semiquantitative picture and a physical interpretation of the process. It is assumed that students have already taken introductory courses in electromagnetic theory, solid-state physics, and quantum mechanics. However, a certain amount of background material has been included so that students who have not taken some of these courses should still be able to follow this text by putting in some extra efforts. Therefore, advanced undergraduate students in engineering and physical sciences, who have already fulfilled sufficient prerequisites, should be able to take this course without much difficulty. It is also my intention to provide general readers with an easy-to-read text, which can help them become acquainted with this subject through self-study.

The first part of the text deals with the principles and applications of optical fibers as data transmission media. Both ray and wave approaches have been employed to explain the mode structures of optical fibers. Special emphasis is given to their interactions and propagation characteristics. The second part reviews and treats in detail the properties and operating characteristics of optical sources and photoreceivers with special emphasis on the emission and regeneration processes in semiconductors and their noise characteristics, which have a great impact on the system performance. The last part is devoted to several applications of these components for data transmission and telecommunication purposes. Efforts are made to present the materials as explicitly as possible. Occasionally, some details are intentionally left out as exercises for students, solely for the purpose of stimulating the learning process.

Fabrication techniques for fibers and other optical components are introduced together with the specific subject matter. A list of problems is included at the end of each chapter. Designs of fiber optical systems are discussed only briefly, because it is difficult to elaborate on topics that are highly specialized and in many cases are still in the development stage. The field that covers the current research on most sophisticated optical devices and circuits is known as integrated optics. It is omitted because its relevance to fiber optical systems is still not clear at this time. Furthermore, no attempt has been made to provide a bank of references or to acknowledge the original work by various contributors. References listed in this text are only those directly related to the subject matter which can provide students with more detailed information. There are many review articles available, most of which provide comprehensive lists of original research papers.

I would like to express my appreciation to Professor W. R. Kolk for his continuing interest and encouragement in this endeavor and to Dr. E. Snitzer, Dr. T. Li, Professor W. S. C. Chang, and to my students, who have made contributions by reducing the number of errors and ambiguities occurring in this text. I wish to express my deep gratitude to my wife, Dorothy, for her unfailing patience in proofreading this text in its entirety. I am also grateful to United Technologies Research Center for providing me with excellent word-processing and illustration services and to the Alcoa Foundation for its interest and support of this project.

Peter K. Cheo
West Hartford, CT

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1

Introduction

Fiber optics has gained prominence in telecommunications, instrumentation, cable TV network, and data transmission and distribution. The major application, however, is in the area of telecommunications. Within this decade, there will be a significant changeover from wires and coaxial cables to optical fibers for telecommunication systems and information services. This anticipated change is dictated almost entirely by economics. The increasing cost and demand for high-data-rate or large-bandwidth-per-transmission channels and the lack of available space in already congested conduits in every metropolitan area are the reasons for this changeover. Furthermore, fiber optical devices interface well with digital data-processing equipment, and their technology is compatible with modern microelectronic technology. For these reasons, it is anticipated that in the future most telephones, television receivers, bank machines, computers, and to a lesser extent, medical and industrial instruments will be linked by optical fibers.

Since 1960 the availability of laser sources has stimulated research into optical communication. However, optical communication was not considered to be practical until 1970, when optical fiber technology had advanced to the point where relatively low-loss (<20 dB/km) fiber could be drawn routinely. Today, fibers with an absorption coefficient $a(\lambda)$ as low as 0.5 dB/km can be manufactured for optical transmission at wavelengths $\lambda \geq 1.2\ \mu$m. For a complete and up-to-date reference list on fiber optics development, readers should consult the review article by Li (Ref. 1.1). General information can be found in two other articles (Refs. 1.2 and 1.3).

A typical optical fiber system linkage is shown in Figure 1.1. The input

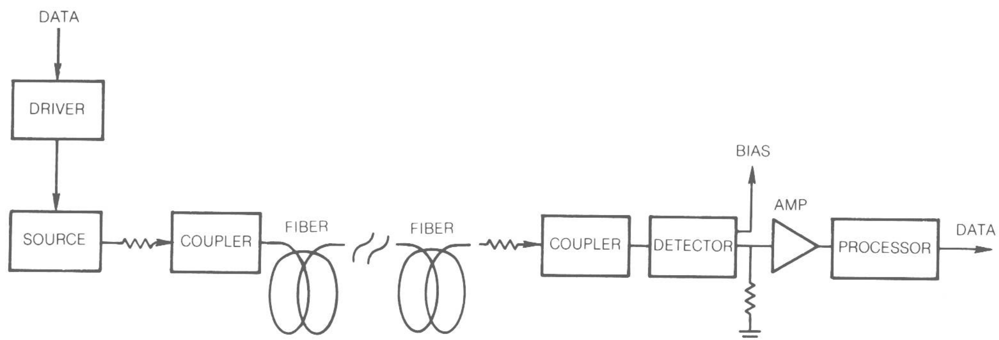

Figure 1.1 Schematic of a typical optical fiber data transmission link.

data are usually coded by using a current pulse network which can directly modulate the light source. The output of light pulses is coupled into a fiber by using a lens or simply a butt joint. The optical power received by the photodiode through a certain length of fiber is always substantially reduced from its initial value due to losses through coupling, absorption, scattering, leakage, dispersion, and mode conversion. To maintain reliable, high-fidelity system operation, the power must be sufficient to overcome system losses. The fidelity of the signals transmitted depends on the detectable level of the signal-to-noise (S/N) ratio, which can be estimated from the detection probability function of a given distribution. For a telecommunication system, the minimum bit error rate (BER) is 10^{-9}, which corresponds to an optical S/N ratio of about 12 dB. The noise equivalent power of an optical receiver used in a typical fiber optical circuit depends on the data rate. Therefore, the minimum required power must be determined by also taking into account the data rate. For an avalanche photodiode, the minimum detectable power, which is equivalent to a S/N ratio of unity, can be as low as -45 dBm at a data rate of 400 megabits per second (Mb/s). System analysis of this type requires knowledge of various parameters that govern the performance of the light source and the detector, the system noise, and propagation characteristics of light in a fiber transmission channel. Various signal processing techniques are required to deal with problems of signal distortion and interference, and statistical methods are often employed to determine system error-detection probability.

This book consists of four main topics: (1) the theory of optical fiber waveguides and pulse propagation phenomena in fibers; (2) the emission process, structure, and performance characteristics of semiconductor light sources; (3) optical receivers and noise characteristics of semiconductor photodiodes; and (4) telecommunication and data transmission systems via optical fibers. It provides a self-contained treatment of these topics so that readers can reach a reasonable level of understanding of the fundamentals without relying too much on other sources for information.

One of the most important components in an optical fiber system is the optical fiber, which is discussed in the next four chapters. In most cases, it is made of glass material (SiO_2) mixed with various dopants primarily to control the refractive index and reduce the softening point. Most fibers have a cylindrical core with an index n_0 of slightly higher value than that of the cladding material n_c. However, some fibers, primarily those made for optical imaging applications, have a square cross section. As shown in Figure 1.2, the radii of the core and the cladding are denoted by a and b, respectively. For a step-index fiber the refractive index is expressed by

$$n(r) = \begin{cases} n_0 & (r < a) \\ n_c & (a \leq r \leq b) \end{cases} \tag{1.1}$$

and for a graded-index fiber with a parabolic profile for its core, the refractive index is expressed by

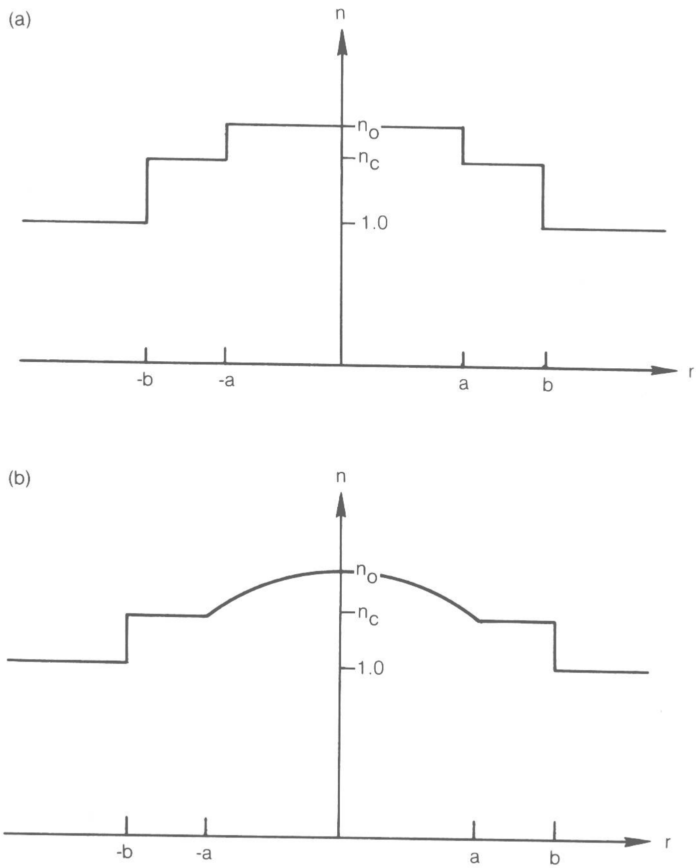

Figure 1.2 Index profile for (a) a step-index fiber having a core diameter $2a$ and clad diameter of $2b$ and (b) a graded-index fiber.

$$n(r) = \begin{cases} n_0 \left[1 - 2\Delta \left(\dfrac{r}{a} \right)^{\alpha} \right]^{1/2} & (r < a) \\ n_c & (a \le r \le b) \end{cases} \tag{1.2}$$

where

$$\Delta = \frac{(n_0 - n_c)}{n_c} \tag{1.3}$$

For a variety of glass fibers with different dopants, $\alpha \simeq 2$.

A single-mode fiber has a core radius typically of the order of one optical wavelength λ. A multimode fiber is one whose core radius is substantially larger than λ and is about 25 to 50 μm. In this case there are hundreds or even thousands of allowable modes propagating in the guide. As a rule, the number of