Fiber-Optic Communication Systems

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Second Edition

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A WILEY-INTERSCIENCE PUBLICATION
JOHN WILEY & SONS, INC.
NEW YORK / CHICHESTER / WEINHEIM / BRISBANE / SINGAPORE / TORONTO

This text is printed on acid-free paper.

Library of Congress Cataloging in Publication Data:

Agrawal, G. P. (Govind P.), 1951-
Fiber-optic communication systems / Govind P. Agrawal. — 2nd ed.
p. cm. — (Wiley series in microwave and optical engineering)
"A Wiley-Interscience publication."
Includes index.
ISBN 0-471-17540-4 (cloth : alk. paper)
1. Optical communications. 2. Fiber optics. I. Title.
II. Series.
TK5103.59.A37 1997
621.382'75—dc21 97-4040

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

For My Parents

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 five years between the two editions. As an example, the highest bit rate of commercial point-to-point links in 1992 was 2.5 Gb/s. By 1996, wavelength-multiplexed systems with a total capacity of 40 Gb/s were available commercially, with the prospect of systems operating at 100 Gb/s or more in sight. In fact, the next transpacific cable (TPC-6), which will transport data at a bit rate of 100 Gb/s, is scheduled to be deployed in 1998 and will be operational by the year 2000. Moreover, three postdeadline papers at the Optical Fiber Communication Conference (OFC'96), held in February 1996 at San Jose, California, demonstrated that lightwave systems operating at a bit rate of 1 Tb/s are within reach by using wavelength-division and time-division multiplexing techniques. Just a few years ago it was unimaginable that lightwave systems would approach a bit rate 1 Tb/s before the end of the twentieth century.

Because of the rapid advances that have occurred in fiber-optic communication technology over the last five years, the publisher and I deemed it necessary to bring out this second edition in order to continue to provide a comprehensive and up-to-date account of fiber-optic communication systems, as stated in the preface of the first edition. 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 as 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 a comprehensive coverage, the book size has increased considerably. Although all chapters have been updated, the major changes have occurred in the last four chapters. Almost half of the material in Chapter 7 is new because of recent advances in the use of wavelength- and time-division multiplexing

techniques for optical networks. Chapter 9 is completely new. It covers a multitude of dispersion-compensation techniques that have been discovered and implemented over the last five years in an attempt to make use of the worldwide installed base of more than 50 million kilometers of standard telecommunication fiber. More than half of the material in Chapter 10 is also new in order to describe the rapid development of soliton-based communication technology. The contents of the book reflect the state of the art of lightwave transmission systems in 1996.

I am acutely aware of the problem caused by an enlarged revised edition: How can a teacher fit all this material in a one-semester course on *optical communications*? I teach such a course to the graduate students of the Institute of Optics at University of Rochester and 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. I can offer my selection as an example. Chapter 3 can be largely skipped, especially if students have taken a laser course previously. Chapter 6 can also be skipped without affecting the continuity. If only parts of Chapters 7 through 10 are covered to provide students a glimpse of recent advances, the material can easily fit in a single one-semester course offered either at the senior level for undergraduates or to graduate students.

Several of my colleagues have helped me in preparing the second edition. I thank R. J. Essiambre, G. R. Gray, and G. H. M. van Tartwijk for reading several chapters and making helpful suggestions. R. J. Essiambre also helped in writing parts of Chapter 10. I am grateful to teachers who adopted this book for their courses and provided occasional feedback. 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
March 1997

Preface to the First Edition

The use of optical fibers for information transmission has become widespread during the decade of the 1980s, as is evident from the installation of fiber-optic telecommunication networks throughout the world. It is further exemplified by the deployment of undersea fiber cables cross both the Atlantic and Pacific oceans. The pace of technological advances in the design of fiber-optic communication systems has been very rapid throughout the 1980s. The trend is continuing during the 1990s, as is apparent from the current emphasis on the research and development of multichannel lightwave systems, erbium-doped fiber amplifiers, and soliton communication systems. An example of how lightwave technology is influencing our society is provided by the recent use of optical fibers by the cable-television industry for analog video distribution through a technique known as subcarrier multiplexing. This change from coaxial cables to optical fibers can increase the transmission capacity by an order of magnitude or more, making it possible to transmit hundreds of video channels to each subscriber. It also enables us to make the transition from analog to digital video, and eventually to high-definition television. Another example is provided by broadband integrated-services digital networks, whose advent is expected to affect the telecommunication industry considerably. Indeed, fiber-optic communication systems can be thought of as an integral part of the information age.

Despite the enormous progress realized in the field of optical fiber communications, it is difficult to convey the sense and importance of this progress to a student or to a scientist who is not an expert in the field. The reason simply is that most of the material is available only in the form of research papers. The objective of this book is to provide a comprehensive, up-to-date account of fiber-optic communication systems in such a way that it can serve as both a textbook and a reference monograph. The emphasis is on physical understanding, but the engineering aspects are also discussed throughout the text.

Many universities in the United States and elsewhere offer a course on optical communications as part of their curriculum in electrical engineering, physics, or optics. I have taught such a course for several years to graduate students at the Institute of Optics. Unfortunately, it is very difficult to find a suitable textbook for the course. Most textbooks on optical fiber communications have become outdated as a result of rapid progress in this growing field. This book is intended to fulfill the acute need for 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 original research papers. A set of problems is included at the end of each chapter to help both teacher and 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 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.

A large number of people have contributed to this book either directly or indirectly. It is impossible to mention all of them by name. I thank the students who took my course on optical communications and helped improve my class notes through interesting discussions. Thanks are due to T. G. Brown and G. R. Gray for reading parts of the manuscript. I appreciate the help of Karen Rolfe, who typed the manuscript and made numerous revisions with a smile. Last, but not least, I thank my wife, Anne, and my daughters, Sipra, Caroline, and Claire, for putting up with my preoccupation with the book, which certainly took away time we could have spent together.

GOVIND P. AGRAWAL

Rochester, NY
March 1992

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