Optical Fibers

Takanori Okoshi

Optical Fibers

TAKANORI OKOSHI
Department of Electronic Engineering
University of Tokyo
Tokyo, Japan

1982

ACADEMIC PRESS
A Subsidiary of Harcourt Brace Jovanovich, Publishers
New York London
Paris San Diego San Francisco São Paulo Sydney Tokyo Toronto

ACADEMIC PRESS, INC.
111 Fifth Avenue, New York, New York 10003

United Kingdom Edition published by
ACADEMIC PRESS, INC. (LONDON) LTD.
24/28 Oval Road, London NW1 7DX

Library of Congress Cataloging in Publication Data

Okoshi, Takanori.
Optical fibers.

Includes index.
1. Fiber optics. 2. Optical communications.
I. Title. [DNLM: 1. Fiber optics. QC 448 O41o]
TA1800.O38 621.36'92 81-17594
ISBN 0-12-525260-9 AACR2

PRINTED IN THE UNITED STATES OF AMERICA

82 83 84 85 9 8 7 6 5 4 3 2 1

Optical Fibers

Preface

The advent of low-loss optical fibers in the early 1970s was a major event in the field of communications in the third quarter of the twentieth century. Since then their design and fabrication techniques have shown exceptionally rapid progress. Engineers now believe that in the distant future the optical fiber will change dramatically the entire aspect of communications in human society.

This book describes the theoretical basis (electromagnetic theories) of transmission characteristics of optical fibers. The material and fabrication technologies are not described systematically, but only briefly where necessary to assist comprehension of the transmission characteristics. The reason for such a restriction is simple: the material and fabrication technologies are still progressing rapidly, whereas the electromagnetic theories have reached in the past several years a level that now enables us to give a textbook-like description on the entire field.

This book is entitled simply "Optical Fibers." If a more lengthy but descriptive title were preferable, it would be "Analysis and Design of Optical Fibers," because most of the description and discussion in this book are motivated by the following two basic questions:

(1) How can we analyze the transmission characteristics (more specifically, the group-delay characteristics, or in other words the modulation-frequency response or the impulse response) of an optical fiber having an arbitrary refractive-index profile?

(2) What is the optimum refractive-index profile with which the group-delay spread of an optical fiber is minimized?

The author never believes, of course, that the readers of this book are concerned only with the analysis of arbitrary-profile fibers or the optimum design of the refractive-index profile. Some readers may be interested mainly in the characteristics of uniform-core fibers, or mainly in the measurement techniques, or even only in the historical aspects of the optical-fiber techniques. To meet such various possible requirements, the author tried to make this a book of as general and comprehensive a nature as possible, still keeping the unity of all the chapters and sections by reminding the readers (and also the author himself) of the above two questions at various steps of the description.

The author and his colleagues started research on optical fibers in 1972. At that time the theories on transmission characteristics of optical fibers had not matured; the relations among different kinds of theories were not well understood, and even worse, different terminologies and symbols were used in different kinds of theories. As the result of the vigorous investigations in the early 1970s, the relations among different theories are now fairly well understood. However, the confusion in the customarily used symbols remains, often annoying investigators and students who study and compare those theories. That was one of the reasons the author and his colleagues wrote the original Japanese edition of this book. It is also the reason the author felt compelled to translate it into English.

The original Japanese edition of this book, "Hikari Faiba no Kiso" (Fundamentals of Optical Fibers), was written jointly by T. Okoshi, K. Okamoto, and K. Hotate, edited by T. Okoshi, and published by the Ohm Publishing Company, Tokyo, in July 1977. The translation of the Japanese text into English began shortly before the publication of the Japanese edition, and was completed in September 1979. In the course of the translation, the author found some chapters and sections unsatisfactory; therefore, he rewrote and supplemented those and reorganized the entire volume.

A bird's-eye view of the construction of this book will be found in Chapter 1, Section 1.4, of the text. For the convenience of readers who have access to both the Japanese and English editions, major revisions will be mentioned in the following. The first half of Chapter 4 has fully been rewritten; the simplest mode theory for a uniform-core fiber is newly added to make the description more comprehensive; Chapter 5 has been thoroughly rewritten and new sections on the power-series expansion method and finite-element-method analyses have been added. The latter half of Chapter 8 has been deleted for space restrictions. Chapter 11 has been updated. Appendixes 2A.1, 3A.1, 3A.2, 3A.4, 3A.5, 3A.6, 4A.1, 4A.2, 5A.4, 5A.9, 5A.10, 5A.11, and 9A.1 have been added.

Acknowledgments

First, I should like to thank the two coauthors of the original Japanese edition of this book, Dr. K. Okamoto, now with Ibaraki Electrical Communication Laboratory, Nippon Telegraph and Telephone Public Corporation (NTT), and Dr. K. Hotate, a lecturer of the Faculty of Engineering, University of Tokyo.

When the manuscript of the Japanese edition was prepared in 1976–1977, both of them were graduate-school Ph.D. students (probably the brightest that I have ever supervised) working on optical fibers in my laboratory. They generously permitted me to translate into English and reorganize the original Japanese edition and to publish the English edition abroad.

I am also indebted to a large number of people for the work on which this book is based. This work was performed with continuous encouragement and support from Professors S. Okamura and H. Yanai, both of the Department of Electronic Engineering, University of Tokyo. Continuous technical support has also been given by Dr. N. Inagaki and others of Ibaraki Electrical Communication Laboratory, NTT; Dr. T. Nakahara and others of Sumitomo Electric Industries, Ltd.; Dr. H. Murata and others of Furukawa Electric Co., Ltd.; and Dr. S. Tanaka and others of Fujikura Cable Works, Ltd. There are also many people from my laboratory at the University of Tokyo who helped me to prepare the figures used and to study the theory of optical fibers by introducing new papers at the weekly seminars of our laboratory.

Writing a book is really a tedious task, especially when the language used is not the author's working language. English was once my working language, but only for a year and half in 1963–1964, when I worked at Bell Laboratories, Murray Hill, New Jersey, on a leave of absence from the University of Tokyo. If the English of this book is a little better than average Japanese English, I owe that difference mostly to my supervisor at Bell Laboratories, Dr. J. W. Gewartowski, who taught me how to write English by correcting carefully all the details of my more than ten technical papers. Moreover, many thanks are due to Professor J. K. Butler of Southern Methodist University, who carefully worked through the entire manuscript to ensure the clarity of language and presentation in English.

Finally, I wish to express my hearty thanks to my secretary, Miss M. Onozuka, who typed the manuscript and its revisions repeatedly. Without her devoted assistance this book would never have been completed.

Contents

4 Wave Theory of Uniform-Core Fibers

5 Wave Theory of Nonuniform-Core Fibers

6 Classification and Comparison of Various Analysis Methods

7 Optimum Refractive-Index Profile of Optical Fibers

8 Optical Fibers Having Structural Fluctuations

9 Measurement of Refractive-Index Profile of Optical Fibers

10 Measurement of Transmission Characteristics of Optical Fibers

11 Concluding Remarks

Appendix

1 Introduction

The history of optical communications rather than that of optical fibers is reviewed. In particular, various optical waveguiding schemes proposed before the advent of practical optical fibers are discussed. Finally, the purpose and organization of this book are stated.

1.1 Technical Background

As early as the 1940s engineers and scientists began to consider that telecommunications in the distant future would be through optical channels. At first such an idea was merely a dream originating from the fact that, since Marconi's invention of wireless telegraphy, radio engineers have continuously pursued technologies of shorter wavelengths. After 1950, however, microwave communications became practical and the definite advantages of using shorter wavelengths were demonstrated. Thus, it became a common belief that the technological push toward shorter wavelengths would reach the optical region.

Nevertheless, until the late 1960s when practical optical fibers appeared, this "common belief" had not been accompanied by a realistic system concept. In reality, it was often asserted that the development of optical communications was inevitable "because it would offer much wider bandwidth per channel than microwave or millimeter-wave channels do since the frequency itself is much higher." Today, this statement is no longer realistic, as seen in the following.

At present, the optical fiber is the only practical waveguide for optical communications. The maximum optical fiber bandwidth imaginable at present is at most several gigahertz, which is much narrower than that of a millimeter waveguide. Optical fiber communications is now being vigorously investigated not because it offers a wide frequency band, but mainly because it offers a wide frequency band at economical costs when many fibers in a bundle are used, thus taking advantage of its flexibility, small diameter, and low cost.

This brief history of optical communications indicates that the advent of practical fibers in the 1960s was really an epochal event in the history of optical communications. It gave the dream of optical communications a realistic system concept and a definite technical target. We will investigate the history of optical communications and illustrate how the optical fiber appeared after various proposals of optical waveguiding schemes.

1.2 Optical Communications Before the Advent of Optical Fibers

In a broad sense, optical communication has a very long history. Even a history of its "practical uses" existed before the history of its research and development in the present century.

1.2.1 First Period—Communication by Eye

The first telecommunication scheme that appeared in the history of man was the most primitive optical communication, signal fire, which has been used by man for thousands of years.

An epoch was marked when Chappe of France invented a new telecommunication scheme, often called the "Semaphore," in 1791 [1]. In his scheme, towers equipped with privoted pointing arms for displaying signals as shown in Fig. 1.1 were constructed at appropriate intervals and manned by operators. Each operator moved the pointing arms in the same manner as he observed on the display of the neighboring tower, and thus messages were transmitted. This was the first high-speed telecommunication system in the history of man, and it had a great impact on European society. The conquest and rule of European countries by Napoleon is said to be in part due to the use of this "optical" communication system.

Chappe's optical communication system disappeared abruptly after the invention of telegraphy by Morse in 1835. Although "optical communications by eye" such as signal flags are still used, their presence is insignificant compared with modern electronic telecommunications. The history of optical communications was once interrupted by the invention of telegraphy in 1835; the history since then is not the history of optical communications but that of the research and development toward its revival.

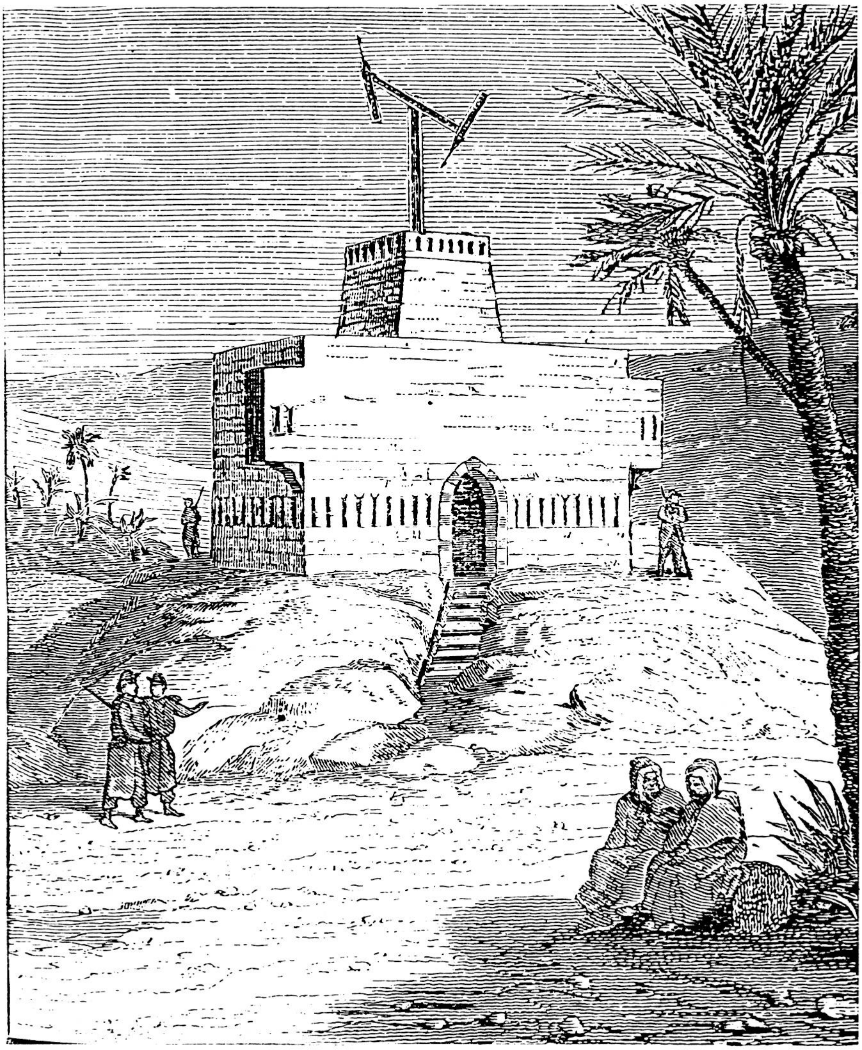

Fig. 1.1 Chappe's communication device (reproduced with permission from "From Semaphore to Satellite" [39]).

1.2.2 Second Period—Optoelectronic Receivers

Before and during World War II, optical communications with higher information-transmission rates using parabolas and phototubes in receivers was investigated for military purposes. However, such systems never became practical before the advent of the laser which was the first light source providing sufficient collimation for such light-transmission schemes.

1.2.3 Third Period—Optical Waveguide Development

The third period began with the advent of lasers in the early 1960s. Because classical microwave technology based on electron tubes and waveguide components was just being completed at that time, many microwave engineers were seeking new challenging tasks. Some went to the fields of microwave semiconductor devices and integrated circuits, and some to the optics field including optical waveguides. As a result, this third period is characterized by their endeavors toward a really practical optical waveguide. Various waveguides such as the hollow metallic waveguide, the thin film waveguide, the lens waveguide, the mirror waveguide, and the gas-lens waveguide were proposed and investigated; however, all of them finally disappeared, as will be described. We should note that preliminary researches on the optical fiber waveguide were also performed in this period.

Various approaches proposed before the advent of practical optical fiber will be reviewed [2]. The history of optical fibers will be described separately later.

A. Iris Waveguide

The simplest among various proposals was the iris waveguide discussed theoretically by Goubau [3] in 1959. As shown in Fig. 1.2, an iris waveguide consists of many optical irises (apertures) placed at equal intervals. Because light energy at the beam edges is repeatedly removed by the irises, the equilibrium state is reached with the fundamental (TEM_{00}) Gaussian mode which has the least loss resulting from the irises.

The theoretical transmission loss of the fundamental mode at the equilibrium state is shown in Fig. 1.3 (curve a) [2]. The abscissa denotes a normalized iris area $S/\lambda d$, where S is the iris area, λ the wavelength of light, and d the iris spacing. For example, when the iris diameter is 3.4 cm, $\lambda =$ 1 μm, and $d =$ 5 cm, the theoretical transmission loss is as low as 1 dB/km. The validity of this theory has been proved by millimeter-wave simulation at $\lambda =$ 8.6 mm by Mink [4].

However, it has also been shown by Mink's experiment that this system requires very high accuracy in positioning irises when the wavelength is short. Moreover, the light path can never be bent without the use of a mirror

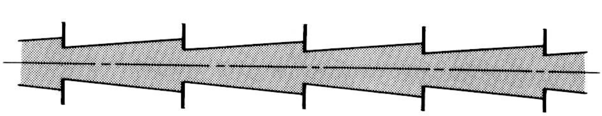

Fig. 1.2 An iris waveguide.

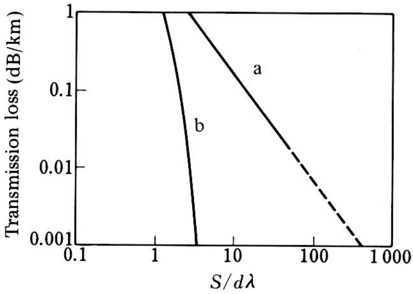

Fig. 1.3 Diffraction loss of (a) iris and (b) lens waveguides (after Gloge [2]).

or prism. Therefore, although theoretically interesting, the iris waveguide is useless for practical applications.

B. Lens and Mirror Waveguides

In an iris waveguide, an incident plane wave gradually diverges due to diffraction. In other words, the wavefront gradually curves. To periodically compensate such wavefront curvature, in 1961 Goubau proposed the structures shown in Figs. 1.4 and 1.5, the lens waveguide and the mirror waveguide [5]. As will be described, such structures have the additional advantage that the light path can be curved by shifting the lenses in the direction normal to the light path or by tilting the mirrors.

When the lens focal length is f, the optimum lens spacing is $d = 2f$. The theoretical transmission loss due to diffraction under this condition is shown in Fig. 1.3 (curve b) [2]. As shown in the figure, the diffraction loss is much lower than that of the iris waveguide, especially when $S/\lambda d$ is relatively large; the loss decreases abruptly as S increases. It is estimated that when S is several times greater than λd, the diffraction loss may be neglected in comparison with reflection loss at lens surfaces, the latter becoming the limiting factor of the transmission loss. We may reduce the reflection loss

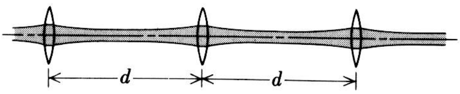

Fig. 1.4 A lens waveguide.

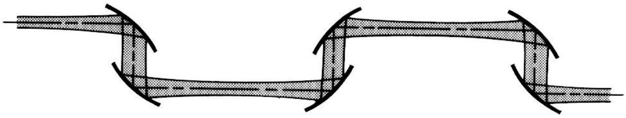

Fig. 1.5 A mirror waveguide.