AN INTRODUCTION TO OPTICAL FIBERS

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PREFACE

The field of fiber optic communications has been a rapidly changing one. Technological advances in the fabrication of optical fibers, interconnection devices, cables, sources, and detectors has propelled a field that was in its infancy in the early 1970s into a major industry of the 1980s. This book is addressed to people who wish to learn about fiber optic communications and emphasizes, in particular, the analysis and technology associated with optical fibers and related fiber optic components. My purpose in writing this book was to provide a textbook for senior level undergraduate and first year graduate engineering and physics students who wish to obtain both a theoretical and practical knowledge of the field of fiber optic communications. I also anticipate that this book will appeal to workers entering this field who want a tutorial introduction to the subject. The material and problems contained in this text have been classroom tested in senior and first year graduate fiber optics courses in the Electrical Engineering Department at the Georgia Institute of Technology.

This book begins with an introductory chapter that provides the reader with a general understanding of the characteristics of optical fibers and how they are used in a communication system. In Chaps. 2 and 3 basic electromagnetic theory is reviewed and the concepts and mathematical models needed to analyze a dielectric waveguide from a wave or ray optics point of view are derived. Chapter 4 deals with the analysis of the dielectric slab waveguide and is included for pedigogical reasons to illustrate how the mathematical models are used to analyze a simple dielectric waveguide. Concepts such as mode cutoff conditions and delay distortion are introduced in this chapter. Chapters 5 and 6 are the heart of the analysis portion of this text. In these chapters the step- and graded-index fibers are analyzed. Propagation conditions for single- and multimode fibers are derived and expressions for many important concepts such as numerical aperture, principal mode number, and delay distortion are developed. The last five chapters of this book consider many of the important applied experimental aspects of fiber optic technology. In Chap. 7 material considerations and fabrication techniques leading to the production of low-loss optical fibers are described. Chapter 8 discusses the techniques used to measure the transmission characteristics of optical fibers. In this chapter the measurement of a fiber's loss, bandwidth, and refractive-index profile are described. Chapter 9 deals with the packaging of optical fibers. The mechanical and optical characteristics of fibers that influence the design of an optical cable are discussed and examples of a variety of different cable designs are given. Chapter 10 is concerned with the coupling of energy from an optical source into a fiber and with the effect that interconnection devices (connectors and splices) have on an optical fiber link. In addition, examples of a number of different interconnection devices are given. Finally, in Chap. 11, general design considerations for fiber optic systems are discussed. Examples of intracity and undersea digital pulse code modulated (PCM) telecommunication systems are given as well as an example of a fiber optic system which transmits video signals using analog modulation of an optical carrier.

I would like to thank Laura Short for her invaluable contributions to the illustrative examples and problems used in this book. I would also like to acknowledge Raye Williams and J. C. Quakenbush for their work in preparing the manuscript of this text. Thanks are also in order to Dr. Terrance Lenahan for his constructive critique of the manuscript and to Professor Demetrius Paris of the Georgia Institute of Technology for his words of encouragement. Finally, I would like to express my appreciation to Bell Telephone Laboratories for supporting this project.

Allen H. Cherin

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ONE

INTRODUCTION TO OPTICAL FIBERS

1-1 INTRODUCTION

Light wave communication systems, using optical fibers as the communications medium, will be an important configuration for transmission networks of the 1980s. Because of the low-loss and high-bandwidth transmission characteristics of optical fibers, they are ideally suited for carrying voice, data, and video signals in a high-information-capacity system. This introductory chapter is intended to give a reader beginning a study of optical fibers a general understanding of what an optical fiber is, how it is used in a communication system, and some of the attractive advantages that an optical communication system has that uses optical fibers as the transmission medium. In addition a very brief historical sketch of optical fiber communication will be given to provide the reader with a perspective from which he can view the current state of the art.

1-2 CLASSIFICATION OF OPTICAL FIBERS

Fibers that are used for optical communication are waveguides made of transparent dielectrics whose function is to guide visible and infrared light over long distances. An optical fiber consists of an inner cylinder of glass, called the core, surrounded by a cylindrical shell of glass or plastic of lower refractive index, called the cladding. Optical fibers (lightguides) may be classified in terms of the refractive index profile of the core and whether one mode (single-mode fiber) or many modes (multimode fiber) are propagating in the guide. If the core, which is typically made of a high-silica-content glass or multicomponent glass, has a

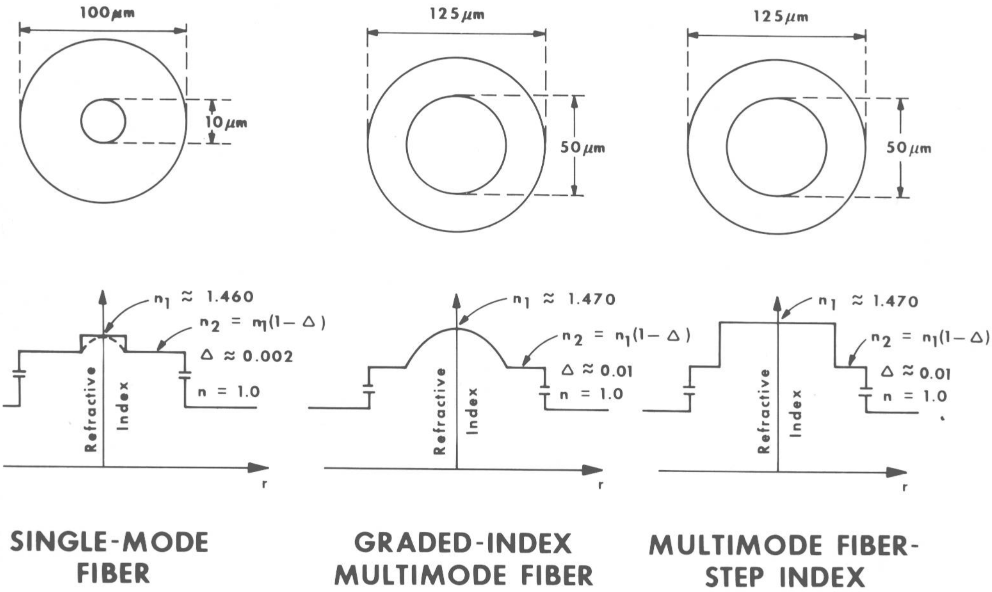


Figure 1-1 Geometry of single- and multimode fibers.

uniform refractive index n_1 it is called a "step-index fiber." If the core has a nonuniform refractive index that gradually decreases from the center toward the core-cladding interface, the fiber is called, a "graded-index fiber." The cladding surrounding the core has a uniform refractive index $n_2 = n_1\ (1 - \Delta)$ that is slightly lower than the refractive index of the core region. The cladding of the fiber is made of high-silica-content glass, multicomponent glass, or plastic. Figure 1-1 shows dimensions and refractive indices for commonly used telecommunication fibers. Figure 1-2 enumerates some of the advantages, contraints, and applications of the different types of fibers. In general, when the transmission medium must have a very high bandwidth, for example in an undersea cable system, a single-mode fiber is used. For intermediate system bandwidth requirements between 200 MHz and 2 GHz-km such as found in intracity trunks between telephone central offices, a graded-index multimode fiber would be the choice. For applications such as data links where lower bandwidth requirements are placed on the transmission medium, a step-index multimode fiber would be used.

1.3 FIBERS IN A SIMPLE COMMUNICATION SYSTEM

This book is primarily concerned with the analysis, fabrication, packaging, joining, and transmission characteristics of optical fibers. It is important, however, for the reader to understand how fibers are used in a communication system.

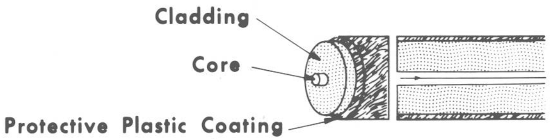
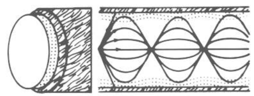
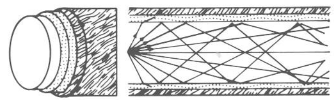
	SINGLE-MODE FIBER	GRADED-INDEX MULTIMODE FIBER	STEP-INDEX MULTIMODE FIBER
			
SOURCE	REQUIRES LASER	LASER or LED	LASER or LED
BANDWIDTH	VERY VERY LARGE > 3 GHz-km	VERY LARGE 200 MHz to 3 GHz-km	LARGE < 200 MHz-km
SPLICING	VERY DIFFICULT DUE TO SMALL CORE	DIFFICULT BUT DOABLE	DIFFICULT BUT DOABLE
EXAMPLE OF APPLICATION	SUBMARINE CABLE SYSTEM	TELEPHONE TRUNK BETWEEN CENTRAL OFFICES	DATA LINKS
COST	LESS EXPENSIVE	MOST EXPENSIVE	LEAST EXPENSIVE

Figure 1-2 Applications and characteristics of fiber types.

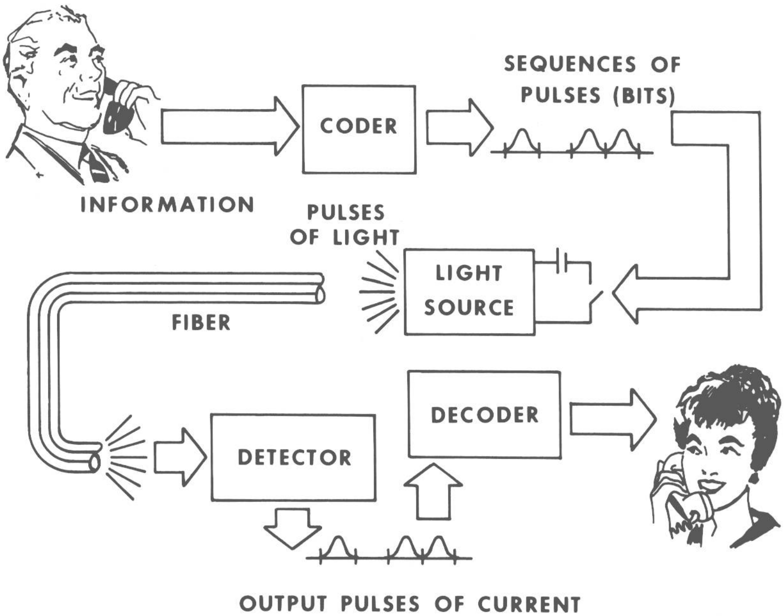


Figure 1-3 Optical system showing telephone call.

Figure 1-3 is a simple example of a telephone conversation being transmitted over an optical communication system. The system consists of a transmitter in the form of a semiconductor laser or light-emitting diode (LED) which is modulated by an information bearing signal. This light source usually radiates in the near-infrared portion of the electromagnetic spectrum (see Fig. 1-4) where the transmission characteristics of optical fibers are best utilized (see Fig. 1-5). The system receiver contains a PIN or avalanche photodiode (APD) that converts the optical signal into an information bearing electrical signal. This electrical signal is then demodulated to produce the audio signal heard in the telephone. The components in this simple system are present in most optical-fiber communication systems in existence today. Figure 1-6 illustrates the basic building blocks of a section of an optical communication system. Detailed examples of optical fiber communication systems will be given in Chap. 11 of this text.

1-4 A BRIEF HISTORICAL REVIEW

It is interesting to note that there is nothing new about using light as the carrier signal in a communication system. In 1880 Alexander Graham Bell invented the photophone.[1] He demonstrated, as shown in Fig. 1-7, that speech could be transmitted on a beam of light. A. G. Bell focused a narrow beam of sunlight onto a thin mirror. When the sound waves of human speech caused the mirror

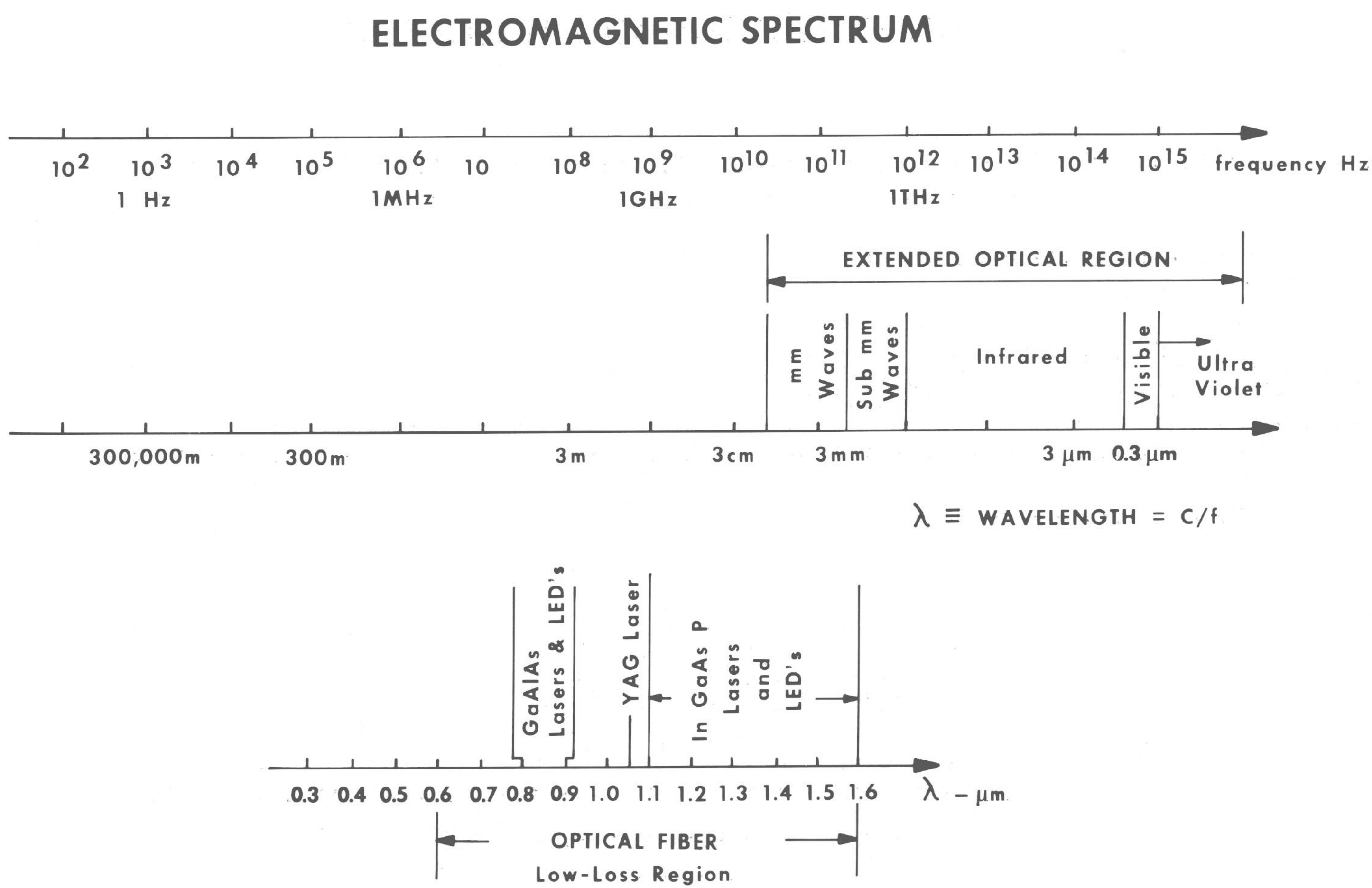


Figure 1-4 Electromagnetic spectrum.

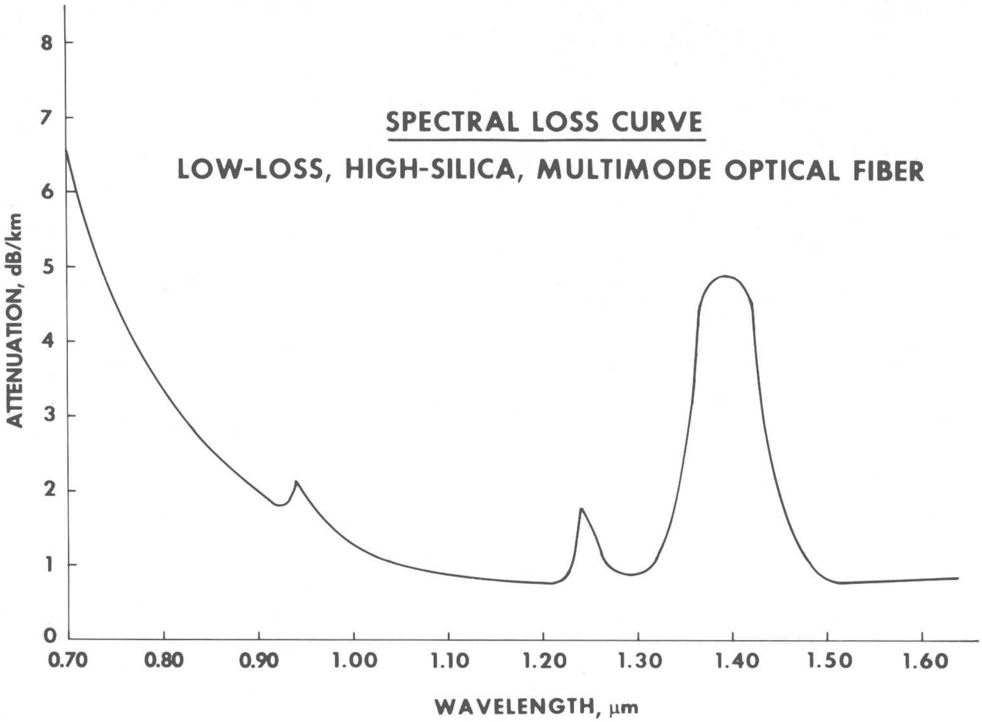


Figure 1-5 Spectral loss curve of optical fiber.

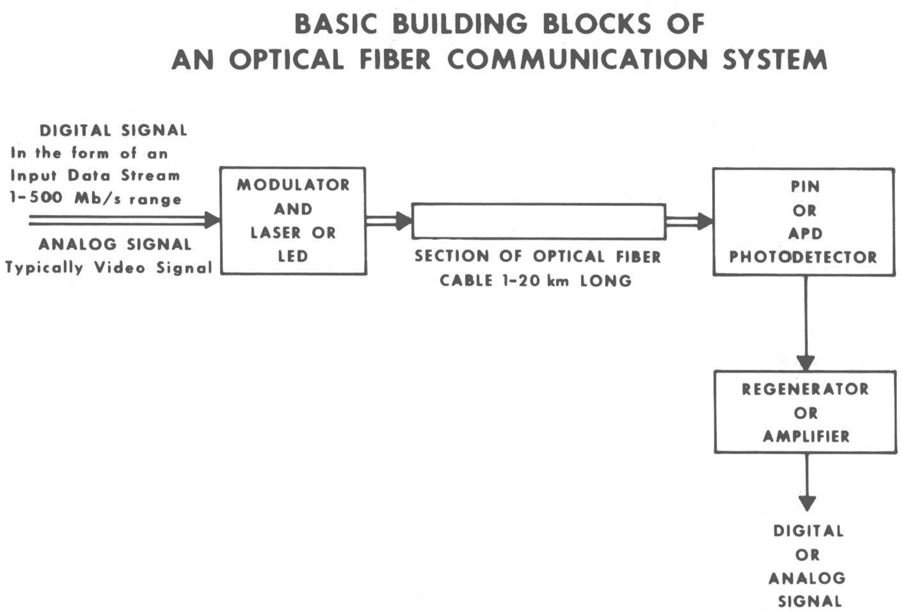


Figure 1-6 Basic building blocks of an optical communication system.

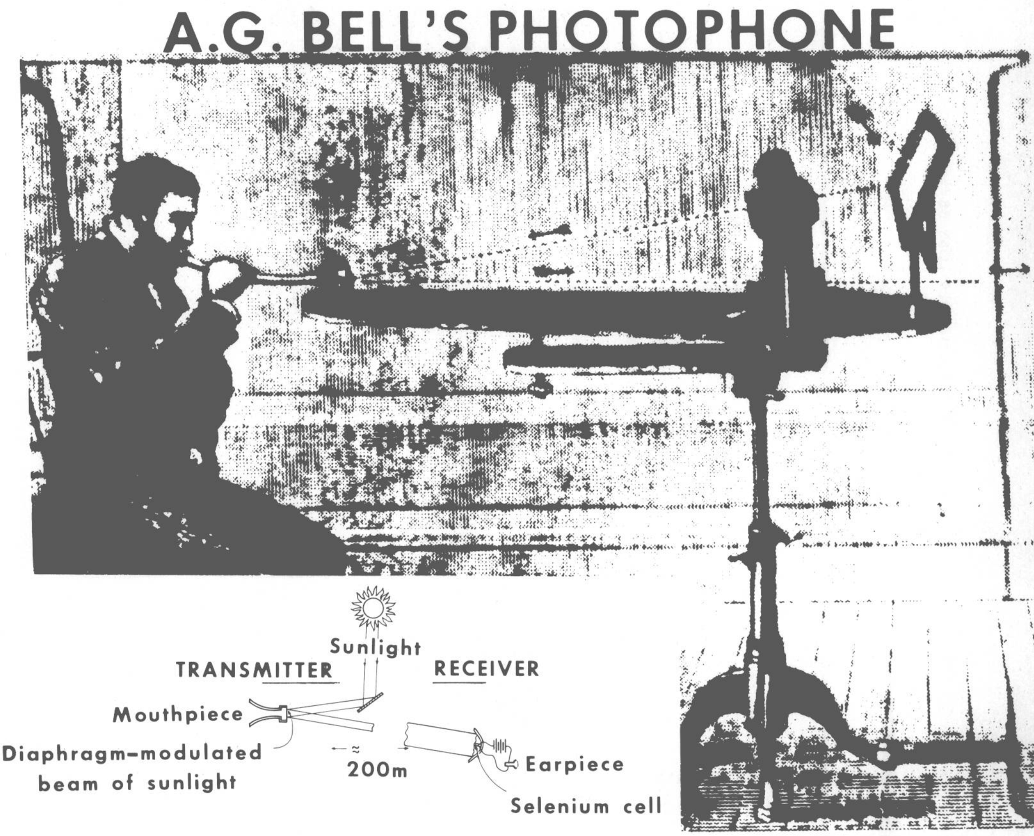


Figure 1-7 Alexander Graham Bell's photophone.

to vibrate, the amount of energy transmitted to the light detector varied correspondingly. The light reaching the selenium detector caused its resistance, and therefore the intensity of the current in a telephone receiver, to vary, setting up speech waves at the receiver end. Bell managed to send voice signals 700 feet by using his ingenious invention.

What is new today, compared to the technology of earlier eras, are the techniques available for generating a light beam that can be modulated at extremely high rates and, equally important, transmitted through a low-loss optical fiber several miles long with acceptable loss of energy.

Modern light-wave communication had its birth in the 1960s. The first demonstration of the ruby laser in 1960[2] followed by a demonstration of laser operations in semiconductor devices in 1962[3,4] were the early stepping stones that led to the continuous operation of room temperature, long life-time, GaAlAs semiconductor lasers that are in common use today. The laser made available a coherent optical frequency carrier on the order of 3×10^{14} Hz. If a