INTRODUCTION TO Fiber Optics

Ajoy Ghatak
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Introduction to fiber optics

AJOY GHATAK   K. THYAGARAJAN

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Preface

The dramatic reduction in transmission loss of optical fibers coupled with equally important developments in the area of light sources and detectors have brought about a phenomenal growth of the fiber optic industry during the past two decades. Indeed, the birth of optical fiber communications coincided with the fabrication of low-loss optical fibers and operation of room temperature semiconductor lasers in 1970. Since then, the scientific and technological progress in the field has been so phenomenal that optical fiber communication systems find themselves already in the fifth generation within a span of about 25 years. Broadband optical fiber amplifiers coupled with wavelength division multiplexing techniques and soliton communication systems are some of the very important developments that have taken place in the past few years, which are already revolutionizing the field of fiber optics. Although the major application of optical fibers has been in the area of telecommunications, many new related areas such as fiber optic sensors, fiber optic devices and components, and integrated optics have witnessed considerable growth. In addition, optical fibers allow us to perform many interesting and simple experiments permitting us to understand basic physical principles.

With the all-pervading applications of optical fibers, many educational institutions have started courses on fiber optics. At our Institute, we have a three-semester M.Tech. program on Optoelectronics and Optical Communications (jointly run by the Physics and Electrical Engineering Departments) in which we have an extensive coverage of the theory of optical fibers and optical fiber communications and also many experiments and projects associated with it. We also have an elective paper on fiber optics for our M.Sc. (Physics) students. The present book is an outgrowth of the lectures that have been delivered both to our M.Sc. as well as to our M.Tech. students during the past fifteen years. Many of the experiments described in the book have also evolved as simple and elegant demonstration of optics principles to our undergraduate engineering students taking a course on Optics. The material presented here and also the associated experiments have been very successfully used in various summer and winter schools in the area of fiber optics conducted by our Institute. It was felt that there is a need today of a textbook at the undergraduate level covering the field from the basic concepts to the very recent advances, including various applications of this exciting field.

The book aims to cover the field of fiber optics and its many applications at an undergraduate level. The book also contains many solved and unsolved problems, some of which will give the reader a greater feel for numbers while the others are expected to help in a greater understanding of the concepts developed in the book. We would greatly appreciate receiving suggestions for further improvement of the book. We would also be very grateful if any errors in the book are pointed out to us.

New Delhi
March 1997

Ajoy Ghatak
K. Thyagarajan

Acknowledgments

It is our most pleasant task to acknowledge the help that we have received from numerous individuals in the writing of this book. We have been working in the general area of guided wave optics for over twenty years and the writing of this book has itself taken over ten years. During this period we have had close interactions with many individuals. In particular, we are deeply indebted to Professor M. S. Sodha (who introduced us to this field) and to our colleagues Professor Ishwar Goyal, Dr. Banshidhar Gupta, Dr. Ajit Kumar, Professor Arun Kumar, Professor Bishnu Pal, Professor Anurag Sharma, Professor Enakshi Sharma, Dr. Raj Shenoy, Dr. Ramanand Tewari and Dr. Ravi Varshney for many enlightening discussions and stimulating collaborations which have enriched our understanding of this exciting field. One of us (AG) used a part of this book in presenting a course of lectures (during the summer sessions of 1987 and 1996) at University of Karlsruhe, Germany. The many stimulating discussions with Professor Gerhard Grau, Professor Wolfgang Freude and Professor Elmer Sauter are gratefully acknowledged.

A major portion of Chapter 11 (on sources for optical fiber communications) was very kindly written by Dr. Raj Shenoy; for this we are very grateful to him. We are also indebted to Mr. Prem Bhavnani, Mr. Rajiv Jindal, Ms. Jagneet Kaur, Mr. Parthasarathi Palai, Mr. K. V. Prakash and Mr. Vipul Rastogi for their help in carrying out many of the detailed calculations and also in the drawing of many figures in the book. Special thanks are due to Mrs. Lata Mathur and Mrs. Bhawna Bharadwaj and also the Continuing Education Program of IIT Delhi for their help and support in the preparation of this book. We are also grateful to Professor V. S. Raju, Director IIT Delhi, for his encouragement and support of this work.

We would like to thank the many authors and publishers for granting us permissions to use their work in this book. In particular, we would like to thank Professor R. R. Alfano and Professor I. Bennion for very kindly providing us with the glossy prints of figures 16.6 and 21.13.

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Abbreviations

Å	Angstrom
APD	avalanche photo diode
ASE	amplified spontaneous emission
AT&T	American telegraph & telephone
BER	bit error rate
BH	buried heterostructure
BW	bandwidth
CCITT	Comite consultatif internationale telegraphique et telephonique
CSF	conventional single mode fiber
cw	continuous wave
dB	decibel
DBR	distributed Bragg reflector
DCF	dispersion compensating fiber
DFB	distributed feedback
DH	double heterostructure
DMA	differential mode attenuation
DSF	dispersion shifted fiber
EDFA	erbium doped fiber amplifier
EMD	equilibrium mode distribution
ESA	excited-state absorption
ESI	equivalent step index
eV	electron volt
e-h	electron-hole
FP	Fabry-Perot
fs	femtosecond
FTIR	frustrated total internal reflection
FWHM	full width at half maximum
FWM	four wave mixing
GHz	gigahertz
GSA	ground state absorption
GVD	group velocity dispersion
GW	gigawatt
HWP	half wave plate
kHz	kilohertz
kV	kilovolt
kW	kilowatt
LCP	left circularly polarized wave
LD	laser diode
LED	light emitting diode
LHS	left hand side
LP	linearly polarized
LPS	limited phase space
Mb/s	mega (million) bits per second
MFD	mode field diameter

MHz	megahertz
MJ	megajoule
MLM	multilongitudinal mode
μm	micron (micrometer)
μs	microsecond
ms	millisecond
MW	megawatt
mW	milliwatt
MZ	Mach-Zehnder
NA	numerical aperture
NA	numerical aperture
NEC	Nippon electric company
NLSE	nonlinear Schrodinger equation
nm	nanometer
ns	nanosecond
PAM	pulse amplitude modulation
PCM	pulse code modulation
PIN	p (doped) intrinsic n (doped)
ps	picosecond
QWP	quarter wave plate
rad	radian
RCP	right circularly polarized wave
RHS	right hand side
rms	root mean square
RNF	refracted near field
RZ	return to zero
SBC	Soleil Babinet compensator
SIF	step index fiber
SNR	signal to noise ratio
SOP	state of polarization
SPM	self-phase modulation
Tb/s	tera (trillion) bits per second
TDM	time division multiplexing
TE	transverse electric
TEM	transverse electromagnetic
TM	transverse magnetic
TNF	transmitted near field
UV	ultra violet
WDM	wavelength division multiplexing
WKB	Wentzel Kramers Brillouin
ZMDW	zero material dispersion wavelength

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1

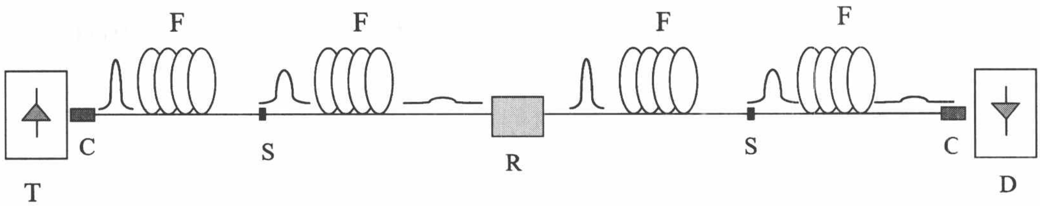
Introduction: The fiber optics revolution

There has always been a demand for increased capacity of transmission of information, and scientists and engineers continuously pursue technological routes for achieving this goal. The technological advances ever since the invention of the laser in 1960 have indeed revolutionized the area of telecommunication and networking. The availability of the laser, which is a coherent source of light waves, presented communication engineers with a suitable carrier wave capable of carrying enormously large amounts of information compared with radiowaves and microwaves. Although the dream of carrying millions of telephone (audio) or video channels through a single light beam is yet to be realized, the technology is slowly edging toward making this dream a reality.

A typical lightwave communication system consists of a lightwave transmitter, which is usually a semiconductor laser diode (emitting in the invisible infrared region of the optical spectrum) with associated electronics for modulating it with the signals; a transmission channel – namely, the optical fiber to carry the modulated light beam; and finally, a receiver, which consists of an optical detector and associated electronics for retrieving the signal (see Figure 1.1). The information – that is, the signal to be transmitted – is usually coded into a digital stream of light pulses by modulating the laser diode. These optical pulses then travel through the optical fiber in the form of guided waves and are received by the optical detector from which the signal is then decoded and retrieved.

At the heart of a lightwave communication system is the optical fiber, which acts as the transmission channel carrying the light beam loaded with information. It consists of a dielectric core (usually doped silica) of high refractive index surrounded by a lower refractive index cladding (see Figure 1.2). Incidentally, silica is the primary constituent of sand, which is found in so much abundance on our earth. Guidance of light through the optical fiber takes place by the phenomenon of total internal reflection. Sending the information-loaded light beams through optical fibers instead of through the open atmosphere protects the light beam from atmospheric uncertainties such as rain, fog, pollution, and so forth.

One of the key elements in the fiber optics revolution has been the dramatic improvement in the transmission characteristics of optical fibers. These include the attenuation of the light beam as well as the distortion in the optical signals as they race through the optical fiber. Figure 1.3 shows the dramatic reduction in the propagation loss of optical radiation through glass from ancient times to present. The steep fall in loss beginning in 1970 as the technology advanced rapidly is very apparent. It was indeed the development of low-loss optical fibers (20 dB/km at the He–Ne laser wavelength of 633 nm) in 1970 by Corning Glass Works in the United States that made practical the use of optical fibers as a viable transmission medium in lightwave communication systems. Figure 1.4 shows the wavelength variation of loss of a typical silica optical fiber showing the low-loss operating wavelength windows of 1300 nm and 1550 nm.

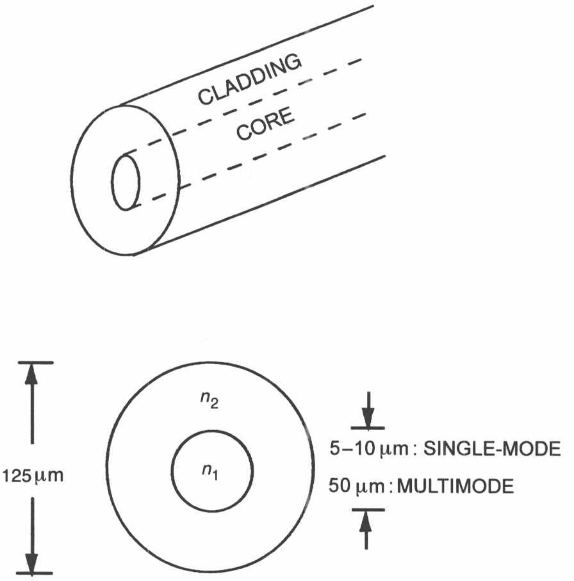


T Transmitter
C Connector
F Fiber
S Splice
R Repeater
D Detector

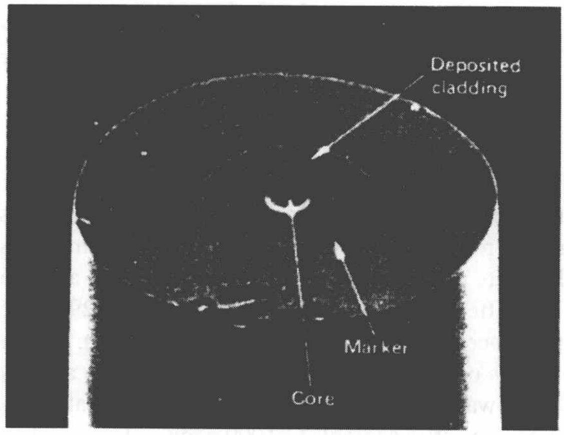
Fig. 1.1: A typical fiber optic communication system consisting of an optical transmitter (laser diode or LED), the transmission medium (optical fiber), and the optical receiver (photodetector). Information is sent in the form of optical pulses through the link.

Although a variety of optical fibers are available, the fibers in most use today are the so-called single-mode fibers with a core diameter of about 10 μm and an overall diameter of 125 μm. Optical fibers with typical losses in the range of 0.2 dB/km at 1550 nm and capable of transmission at 2–10 Gbit/s (Gb/s) are now commercially available. (A loss figure of 0.2 dB/km would imply a 50% power loss after propagating through a distance of about 15 km; the corresponding power loss for the best glass available in 1966 was about 1000 dB/km, which implies a 50% power loss in a distance of about 3 m!) Most currently installed systems are based on communication at a 1300-nm optical window of transmission. The choice of this wavelength was dictated by the fact that around an operating wavelength of 1300 nm the optical pulses propagate through a conventional single-mode fiber with almost no pulse broadening. Because silica has the lowest loss in the 1550-nm wavelength band, special fibers known as dispersion-shifted fibers have been developed to have negligible dispersion in the 1550-nm band, thus providing us with fibers having lowest loss and almost negligible dispersion.

In the lightwave communication systems in operation today, the signals have to be regenerated every 30–60 km to ensure that information is intelligibly retrieved at the receiving end. This is necessary either because the light pulses have become attenuated, and hence the signal levels have fallen below the detectable level, or because the spreading of the pulses has resulted in an overlapping of adjacent pulses leading to a loss of information. Until now this regeneration had to be achieved by first converting the optical signals into electrical signals, regenerating the signals electrically, and then once again converting the electrical signals into optical signals by modulating another semiconductor laser; such devices are called regenerators. Recent developments in optical amplifiers based on erbium- (a rare earth element) doped silica optical fibers have opened up possibilities of amplifying optical signals directly in the optical domain without the need of conversion to electrical signals. Because of amplification in the optical domain itself, such systems are not limited by the speed of the electronic circuitry and indeed can amplify multiple signals transmitted via different wavelengths simultaneously. For example, Figure 1.5 shows a typical gain spectrum of an erbium-doped fiber amplifier where one can note the flat gain over a wavelength band as large as 30 nm. Fortuitously, the gain band of



(a) MATERIAL : DOPED SILICA



(b)

Fig. 1.2: (a) A typical optical fiber consisting of a doped silica core surrounded by a pure silica cladding of slightly lower refractive index. Light guidance takes place through the phenomenon of total internal reflection. (b) A scanning electron micrograph of an etched fiber showing clearly the core and the cladding. [After Miya et al. (1979).]

such optical amplifiers falls exactly on the low-loss transmission window of silica-based fibers. Indeed, the wavelength band of 100 nm around 1550 nm of the low-loss window of silica-based optical fibers (from 1500 to 1600 nm) corresponds to 12,500 GHz of bandwidth. This may be compared with the total radio bandwidth of only 25 GHz. Although these give the total accessible bandwidth figures, utilizing even a fraction of this available bandwidth gives us an enormous potential.

The coincidence of the low-loss window and the wide-bandwidth erbium-doped optical amplifiers has opened up possibilities of having wavelength division multiplexed communication systems (i.e., systems in which multiple wavelengths are used to carry independent signals, thus multiplying the

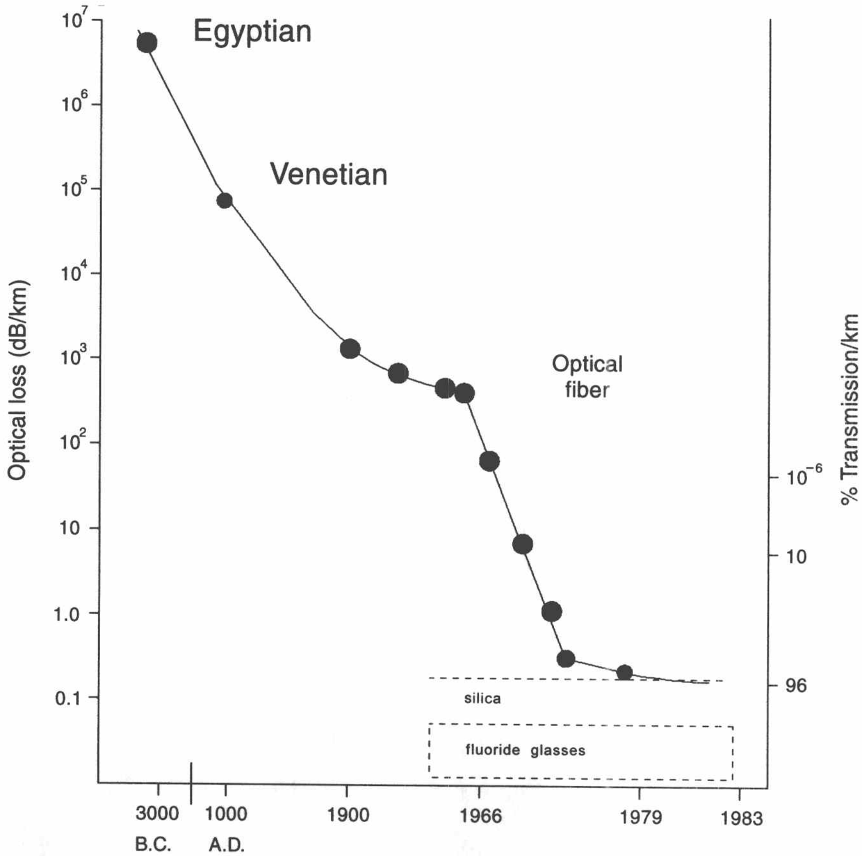


Fig. 1.3: Figure shows the dramatic reduction in transmission loss in optical glass from ancient times to present. [After Nagel (1989).]

capacity of an individual fiber) capable of carrying enormous rates of information. Indeed, recent reports have shown successful transmission at the rate of 1.1 trillion bits per second (1.1 Tb/s) over 150 km and 2.6 Tb/s over 120 km using 132 different wavelengths in the interval 1529.03–1563.86 nm (European Conference on Optical Communication, 1996). Figure 1.6 shows the setup and results of the 1.1-Tb/s experiment that were accomplished with 55 different optical wavelengths carrying independent signals. This corresponds to sending almost the entire contents of 1000 copies of a 30-volume encyclopedia in 1 s!

There is also a lot of research activity on special kinds of fibers – namely, dispersion-compensating fibers (DCFs). This has arisen because the existing underground network already contains more than 70 million km of fibers optimized for operation at 1300 nm. Because today's optical amplifiers operate only in the 1550-nm region, the question that arises is whether it is possible to use the existing network of fibers to send signals at 1550 nm. Since they are not optimized for 1550-nm operation, such fibers exhibit a significant amount of dispersion at 1550 nm, leading to distortion of signals. The newly developed DCFs have very large dispersions but have a sign that is opposite those of the 1300-nm fibers. Hence, by appropriately choosing the lengths of these fibers, one can indeed compensate for the distortion and thus use the