# Fiber Optic COMMUNICATIONS

Lynne D. Green

# Fiber Optic COMMUNICATIONS

Lynne D. Green
President
Green Streak Programs
Woodinville, Washington



CRC Press
Boca Raton Ann Arbor London Tokyo

Photo credit: cover photograph #C000-07835-286 Comstock Inc./Michael Stuckey.

**Library of Congress Cataloging-in-Publication Data**

Green, Lynne D.
Fiber optic communications/Lynne D. Green.
p. cm.
Includes bibliographical references and index.
ISBN 0-8493-4470-0
1. Optical communications. 2. Fiber optics. I. Title.
TK5103.59.G737 1992
621.382'75—dc20 92-36600
CIP



Direct all inquiries to CRC Press, Inc., 2000 Corporate Blvd., N.W., Boca Raton, Florida, 33431.



International Standard Book Number 0-8493-4470

Library of Congress Card Number 92-36600

Printed in the United States of America 1 2 3 4 5 6 7 8 9 0

Printed on acid-free paper

This book is dedicated to those who helped to make it possible. First and foremost is my husband, Kelly Green. Contributions were also made by students and staff at Cogswell College North. The students provided numerous helpful comments while using an early draft as a text. Finally, but by no means least, thanks are due the editors at CRC Press, who brought this book to the light of day.

# PREFACE

This book is an outgrowth of fiber optic design courses given by the author. The focus of the text is the practical design of point–to–point fiber optic links, and is addressed to practicing engineers and students in electrical engineering and electronics technology. The background needed for this material includes engineering mathematics, college physics, and a basic knowledge of analog transistor circuits. A reading list is provided for those desiring to pursue any topic in greater depth.

The text is designed for a senior design–oriented course. It is also suitable for self–study, with numerous examples and a variety of exercises provided. Related topics, such as Maxwell's equations, are included in appendices, together with related exercises.

Applications of fiber optics to digital communications, analog and digitized video, and related areas are discussed. The examples illustrating design equation usage and design techniques draw from these application areas. Design equations are given in the body of the text, together with discussions of their ranges of validity and examples. Typical parameters are used for link components in the examples and the exercises. Component characteristics and design techniques are discussed with a focus towards practical design of fiber optic links.

Components are covered with emphasis on performance within a system. For example, the effect of source spectral width on system bandwidth is discussed in three places: the chapter on modules, the chapter on fibers, and the chapter on design techniques.

## A NOTE ON UNITS

SI (MKSA) units are used throughout the book, following standard industry practice. The exception to this rule is for link lengths, which are normally given in either miles or kilometers. A table of physical constants and unit conversions is found in the appendices.

Where industry practice uses standard prefixes, these are also used herein. For example, the wavelength of light is usually given in either nm or μm (e. g. 1.3 μm or 1300 nm), while link lengths are given in km. The reader is encouraged to perform both dimensional and prefix analysis in the exercises as one way of becoming more familiar with the orders of magnitude of typical values encountered in fiber optic link design.

### Table of Metric Prefixes

| Prefix | Name | Power |
|---|---|---|
| T | tera | $10^{+12}$ |
| G | giga | $10^{+9}$ |
| M | mega | $10^{+6}$ |
| k | kilo | $10^{+3}$ |
| m | milli | $10^{-3}$ |
| μ | micro | $10^{-6}$ |
| n | nano | $10^{-9}$ |
| p | pico | $10^{-12}$ |
| f | femto | $10^{-15}$ |

# Table of Contents

**Chapter 1 Historical Perspective** .......... 1
1.1: Fiber Optic Technology Evolution 1
1.2: Comparison to Free Space and Coax Systems 4
1.3: Technology and Application Trends 8
1.4: Market Trends 10
1.5: Summary 13
1.6: Exercises 13

**Chapter 2 Network Overview** .......... 15
2.1: The OSI Model 16
2.2: The Physical Layer 19
2.3: Data Coding Techniques 19
2.4: The Role of Standards 23
2.5: Network and Data Timing 24
2.6: Measures of Link Performance 27
2.7: Summary 30
2.8: Exercises 30

**Chapter 3 Optics and Materials** .......... 33
3.1: Light 33
3.2: Geometric Optics 35
3.3: Wave Optics 37
3.4: Summary 40
3.5: Exercises 41

**Chapter 4 Transmitters** .......... 43
4.1: Transmitter Overview 44
4.2: The Electrical Interface 46
4.3: Multiplexing Schemes 46
4.4: Modules and Discrete Designs 48
4.5: LED and Laser Diodes 49
4.6: LED Devices 51
4.7: Laser Devices 55

4.8: Device Biasing 56
4.9: Environmental Effects 57
4.10: Reliability 61
4.11: LED vs. Laser: System Tradeoffs 62
4.12: Summary 66
4.13: Exercises 66

**Chapter 5 Receiver Modules** .......... 69
5.1: Receiver Overview 69
5.2: Device Structures 70
5.3: Amplifiers 76
5.4: Receiver Bandwidth 80
5.5: Receiver Noise Performance 83
5.6: Environmental Effects 87
5.7: Receiver Layout 88
5.8: Summary 89
5.9: Exercises 90

**Chapter 6 Optical Fiber Characteristics** .......... 93
6.1: Fiber Profiles 94
6.2: Waveguide Properties 96
6.3: Optical Interface 98
6.4: Attenuation 100
6.5: Bending Losses 104
6.6: Connection Losses 107
6.7: Splices And Connectors 112
6.8: Optical Multiplexing 114
6.9: Fiber Amplifiers 116
6.10: Summary 118
6.11: Exercises 118

**Chapter 7 Link Bandwidth** .......... 121
7.1: Link Transfer Function 121
7.2: Intermodal Dispersion 123
7.3: Intramodal Dispersion 125
7.4: Total Fiber Dispersion 128
7.5: Link Bandwidth 129

7.6: Non–linear and Harmonic Effects 130
7.7: System Tradeoffs 132
7.8: Summary 133
7.9: Exercises 134

**Chapter 8 Link Analysis** ........ 137
8.1: Components 138
8.2: Link Power Analysis 139
8.3: Digital Links 142
8.4: Analog Links 144
8.5: Wavelength Division Multiplexing 147
8.6: Summary 148
8.7: Component Library for Exercises 148
8.8: Exercises 149

**Chapter 9 Link Design** ........ 153
9.1: Window Selection 154
9.2: Module Selection 156
9.3: Fiber and Cable Selection 157
9.4: Performance Analysis 158
9.5: Summary 161
9.6: Exercises 161

**Chapter 10 Installation and Testing** ........ 163
10.1: Component Acceptance Testing 163
10.2: Link Acceptance Testing 165
10.3: Test Equipment 166
10.4: Link Reliability 169
10.5: Installation Techniques 169
10.6: Troubleshooting Techniques 171
10.7: Summary 173
10.8: Exercises 173

**Appendix A Bibliography** ........ 175

**Appendix B Glossary** ........ 177

**Appendix C Symbols, Constants, and Conversions** ........ 179

**Appendix D Signals and Noise** .......... 185
D.1: Exercises 188

**Appendix E Maxwell's Equations** .......... 189
E.1: Maxwell's Equations: Free Space 191
E.2: Maxwell's Equations: Rectangular Metal Waveguide 193
E.3: Maxwell's Equations: Circular Dielectric Waveguide 195
E.4: Exercises 197

**Appendix F Frequency Response** .......... 199

**Appendix G Semiconductor Materials** .......... 201

**Appendix H Power and Risetime Budget Sheets (Blanks)** .......... 205

**Index** .......... 207

# Chapter 1 Historical Perspective

## 1.1: Fiber Optic Technology Evolution

Optical communications have been used since early times. Primitive optical communications over free space included the use of signal fires, an early form of digital (one–bit) communication. Polybius, a Greek, later improved on this, using the arrangement shown in Figure 1-1 to spell out words, allowing the transmission of brief messages. Early optical communications were characterized by low information transfer rates and by free space transmission.

Little improvement occurred in optical communications until the 17th century. Isaac Newton [1642–1727], Robert Boyle [1627–1692], and Christiaan Huygens [1629–1695], among others, performed experiments to determine the nature of light throughout the 1600's and early 1700's. Newton discovered dispersion, showing that sunlight was composed of a spectrum of colors. In 1800, William Herschel [1738–1822] discovered infrared energy in sunlight.

Augustine–Jean Fresnel [1788–1827] developed the first detailed mathematical theory of the wave properties of light. He explained for the first time the diffraction effects first observed by Francesco Grimaldi [1618–1663]. Interference effects (e. g. the double–slit experiment) are used today in physics classes to demonstrate the wave properties of light.

The photoelectric effect, observed by Heinrich Hertz [1857–1894] in 1887, showed that light is composed of particles or packets of energy (photons). The cause of the photoelectric effect was explained by Albert

Einstein [1879–1955] in 1905, and he received the Nobel Prize in 1921 for that discovery.

| | | | | |
|---|---|---|---|---|
| α | β | γ | δ | ε |
| ζ | η | θ | ι | κ |
| λ | μ | ν | ξ | ο |
| π | ρ | σ | τ | υ |
| φ | χ | ψ | ω | |

TORCH PATTERN
Example: μ = Row 3, Col 2

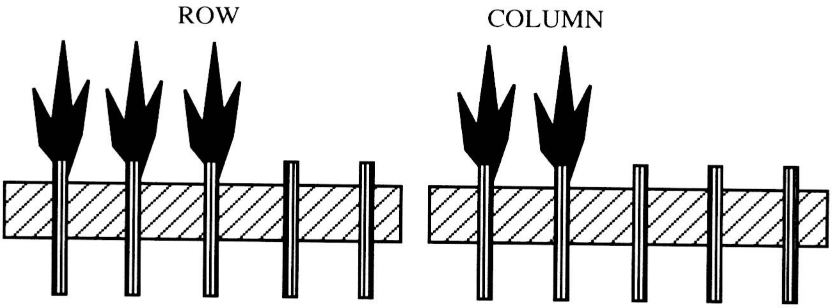


**Figure 1-1: Early Greek Optical Communications.**

With the development of quantum mechanics in the 1930's, it was realized that light, as well as electrons and other classical particles, have both particle properties (speed, momentum) and wave properties (wavelength, energy). For photons, the wave properties generally dominate, since their rest mass is zero. Quantization (particle) effects become noticeable when photons interact with electrons (as in the photoelectric effect).[1]

Telecommunications began to achieve commercial viability in the 1800's. Samuel Morse [1791–1872] developed a wire–based telegraph in 1838. The telegraph was a digital (short/long pulse) system. Radio operators today still learn the Morse code. The first telephone exchange began operations in 1878.

[1] For classical particles, the particle properties generally dominate, since the speed is much less than that of light. However, wave effects become noticeable when fast particles are diffracted, as in a double slit experiment using electrons.

Maxwell's equations, presented by James Clerk Maxwell [1831–1879], unified the electric and magnetic field concepts of his day. Hertz observed radio waves generated by electric currents in his laboratory. Guglielmo Marconi [1874–1937] made the first demonstration of radio transmission. These led to the development of wireless telegraphy, and later radio communications. Today, free space transmission is used for many transmission systems, such as cellular radio, TV, microwave, and satellite communications.

The concept of guided optical waves is more recent. Total internal reflection of light in a beam of water was demonstrated by John Tyndall [1820–1893] in 1854, but no practical applications for communications were identified at that time. Alexander Graham Bell [1847–1922] invented the photophone in 1880, in which an optical signal was modulated by a membrane which vibrated in response to sound waves in air. Again this was a free space transmission system. The major element in this invention was the movement of a reflective membrane due to audio pressure waves in air.

The first patent on guided optical communications over a transparent medium (glass) was obtained by AT&T in 1934. Light–emitting diode action had been observed in 1923 by O. V. Lossew, and photodetectors even earlier, but these were in use mainly as instrumentation devices. In 1934, there were no transparent materials with sufficiently low attenuation to make the technology feasible. It was not until the 1960's that the proposed systems could be assembled in a laboratory with practical components.

Optical technology took several major strides forward in the 1960's. The gas laser was proposed in 1958 and developed in 1960, and diode laser action was reported in 1962. Meanwhile, a better understanding of loss mechanisms in glass fiber was being developed. Between 1968 and 1970, the attenuation of glass fiber dropped from over 1000 dB/km to less than 20 dB/km, and Corning patented its fiber making process. The combination of diode lasers and low-loss glass fibers allowed fiber optic communications systems to be developed beginning in the early 1970's.

A wide range of new application areas opened up in the 1980's, as the cost of fiber and transmitter / receiver sets decreased dramatically. In addition to telecommunications and local area networks, fiber optic links can now be found in everything from automobiles to compact disc players. Fiber optic links are also used in instrumentation systems, where they provide immunity from EMI noise.

The optical fiber or active optical component can serve as the sensor, providing novel ways to measure chemical and physical properties. Fiber optic sensors are often smaller, lighter, and faster to respond than other sensors. The pH sensor shown in Figure 1-2 uses an optical fiber to transmit light to a reflective medium and to return the reflected light back to the instrumentation system. This sensor can be used in place of litmus paper, and can be used more than once. Many sensors on the market today include autocalibration and digital read–outs, making them suitable for automated measurements.

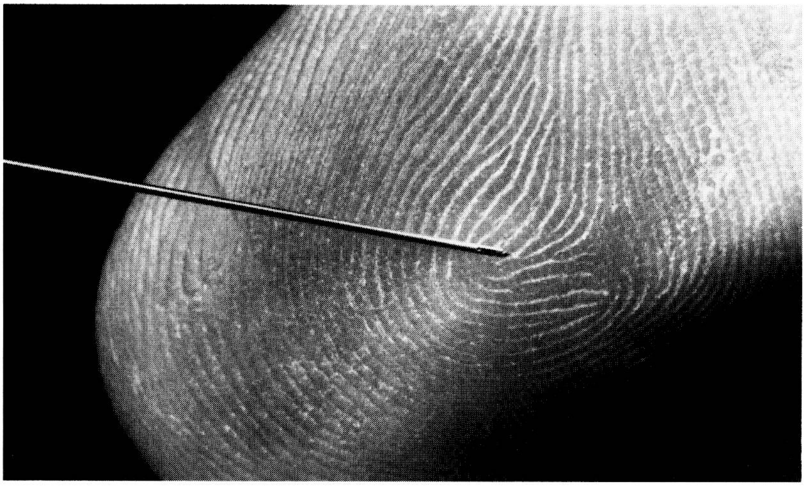

**Figure 1-2: A pH Sensor.**
The active volume of this sensor is in the "eye" of the needle. *Courtesy of Research International, Inc.*

## 1.2: Comparison to Free Space and Coax Systems

Fiber optic communications offers several significant advantages over the alternatives. Unlike TV and other free space transmission systems, there is no problem of bandwidth allocation or restrictions. In the United States today, for example, the only way to start a new TV station in any major metropolitan area is to buy an existing station. Frequency assignments are allocated by the FCC (Federal Communications Commission) for all communications ranges (TV, radio, microwave, cellular telephones, etc.). The FCC regulations cover carrier frequency assignments, EMI limits, and modulation (e. g. AM/FM and HDTV).

The major advantages of fiber optics over wire systems are the low attenuation and high bandwidth available using glass fiber. Because attenuation is low, longer distances can be spanned between repeaters. Because attenuation is independent of frequency over a wide bandwidth, equalization becomes less important. Figure 1-3 shows the attenuation characteristics of coax and fiber. For high–quality glass fiber, the attenuation curve remains flat beyond 1 GHz.

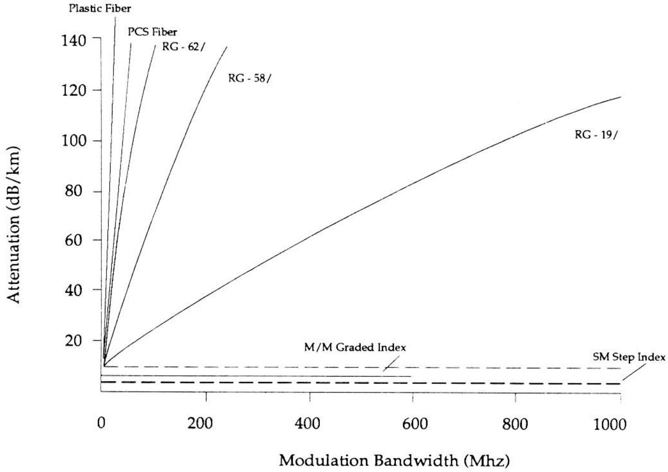


**Figure 1-3: Attenuation vs. Frequency.**

A comparison of the attenuation of coax and fiber. The fiber has both a lower loss and a flatter frequency dependence. *Courtesy of The Light Brigade Inc.*

For communication of information, there are other advantages as well. With a dielectric (glass or plastic) medium, there are no external electromagnetic fields. Therefore, there is no crosstalk between fibers or EMI (electromagnetic interference) radiated into space. For high bandwidth systems, multiple fibers can be run close together, since there is no crosstalk. For military, banking, and other information systems where data security is important, the lack of EMI provides a system that cannot be tapped with inductive coupling.[1] Dielectric fiber optics prevents emissions from the carrier medium (although it does not prevent board-level emissions).

Because the signal remains completely within the fiber, each user is isolated not only from other users, but also from regulatory agencies. In a fiber optic system, the user is free to select a carrier frequency (or wavelength) and modulation scheme that best fit the system requirements. Regulations and

[1] EMI emission problems can lead to expensive fines. In 1990, for example, one company was fined $4000 for exceeding FCC emission limits for just 2 days; these emissions interfered with a nearby air control tower.

standards are imposed by system requirements rather than by an outside agency.

Fiber optics also presents a number of advantages for industrial and transportation applications. In automated factories, for example, robot systems create severe EMI environments. Robot motors switch large currents through inductive wires, which in turn couple into data network wiring. Data transmission systems can then interpret these signals as false data. Because fiber optics uses a dielectric medium, the EMI signals are not coupled into the fibers, and the data is not corrupted. The dielectric fiber also presents a safety enhancement, since it does not carry current or electrical power. The lack of current means that there is no shock hazard to personnel, and there is no danger of an intermittent open circuit causing a spark. Spark ignition can cause fires and explosions in chemically active environments; these are a prime area for application of fiber optics.

In transportation, the small size and light weight of optical fiber offers a significant advantage. A fiber system may weigh 30 times less than an equivalent copper system. This is also an advantage in city and building ducts, where a 3–in. 900–pair copper cable can be replaced by a single pair of optical fibers with an increase in performance. Figure 1-4 shows the size comparison between this wire cable and an optical fiber. In telecommunications wiring, the copper cable can be replaced with a 144–fiber bundle capable of carrying 245 Gbit/sec. Table 1-1 shows how the wire and fiber cables compare for size, weight, speed, and cost for cables suitable for underground burial. Note that cost varies with year; in 1989 the cost of copper doubled, while the price of fiber decreased.

Cost is the major drawback of fiber optics. For example, connector costs have dropped dramatically, but they continue to be more expensive than twisted pair or coax connectors. Similarly, the cost of fibers, transmitters, and receivers remains somewhat higher than corresponding components for wire-based systems, although the difference is steadily decreasing. For short systems (less than 200 ft.), and for low speed systems (less than 1 Mbit/sec), fiber optics offers little advantage over wire systems.

The cost of a typical telecommunications fiber bundle is seen to be higher than that of copper in Table 1-1. The cost per equivalent telephone circuit-mile, however, is significantly less for a fiber–based system. For large information volumes and/or long distances, the cost advantages of fiber optics are clear. An absolute data rate and distance for the cost break–even point cannot be given, since prices for optical systems are dropping rapidly. Systems costs have dropped as fast as 30% per year, and some active component costs have dropped over 40% in one year.

Although fiber optics offers greatest advantages at long distances and high data rates, the recent introduction of improved plastic fibers has also brought fiber optic networks down to the small office. Plastic fiber can be used to interconnect PCs, printers, and scanners at a cost comparable to that of copper systems, even at relatively short distances. These plastic fiber systems illustrate the tradeoff between cost and performance, being less costly and operating at significantly lower distance and data rates than glass fiber systems.

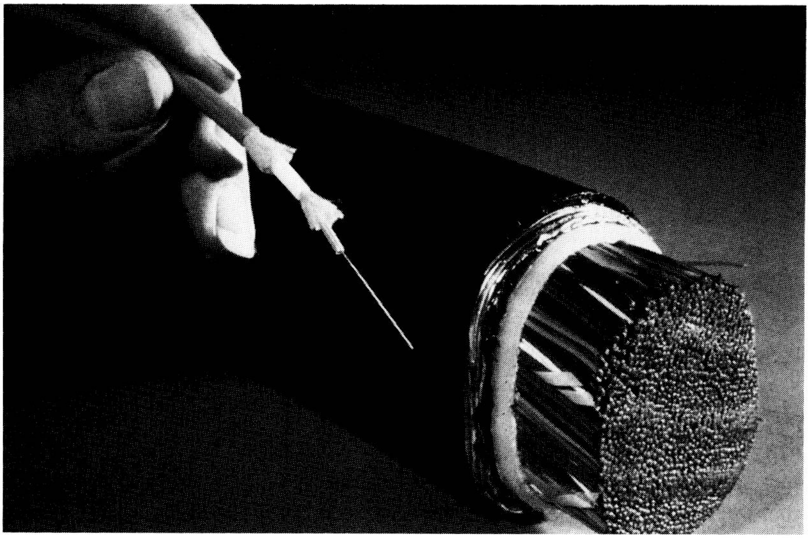

**Figure 1-4: Wire Cable and Fiber.**

A 900–pair copper cable and a single fiber. The fiber is capable of carrying all of the information of the entire cable. *Photograph courtesy of Corning, Inc.*

A fiber optic system designer may deal with outside agencies when connecting a private system to a larger network. In particular, the telecommunications companies (e. g. AT&T) and other public and private utilities have their own fiber optic network standards. It is possible to lease "dark" (unused) fibers, or to multiplex data onto high-bandwidth lines. For example, the first frame level service was offered to telecommunication users in 1991. Careful attention to the interface standards must be paid if systems integration is to proceed smoothly.