Fundamentals of Optical Fiber Communications

Wim van Etten and Jan van der Plaats

Eindhoven University of Technology, The Netherlands
Contents

Preface xi

1 Introduction 1
   1.1 The configuration of a glassfiber 4
   1.2 The manufacture of fibers 6
   1.3 The attenuation of light in glassfibers 9
   1.4 Light sources 13
   1.5 Detectors 17
   1.6 System model 17
       References 18
       Problem 19

2 Analysis of the slab waveguide 20
   2.1 Theoretical models 20
   2.2 The slab waveguide analyzed with wave optics 21
   2.3 Transverse electric waves 22
   2.4 Transverse magnetic waves 28
   2.5 The propagation constant of a mode 28
   2.6 Geometric optics interpretation 29
       References 32
       Problems 32

3 Analysis of the step index fiber 33
   3.1 The general solution of the wave equation 34
   3.2 Unattenuated waves 36
   3.3 Transverse and hybrid waves and modes 40
   3.4 Transverse waves and modes 40
   3.5 Hybrid modes 45
   3.6 Leaky modes 52
   3.7 Linearly polarized (LP) modes 52
       References 58
       Problems 58

4 Dispersion in the step index fiber 60
   4.1 Phase characteristic and modulation bandwidth 62
### Contents

- **4.2** The propagation constant of a mode in a step index fiber 68
- **4.3** Waveguide dispersion 69
- **4.4** Material dispersion 72
- **4.5** Waveguide and material dispersion in a step index fiber 73
- **4.6** Multimode dispersion 75
- **4.7** Dispersion caused by a non-monochromatic source 76
  - References 76
  - Problems 76

5 **The monomode fiber** 78

- **5.1** The electromagnetic field in a monomode step index fiber 79
- **5.2** Power flow in the z-direction 84
- **5.3** The mode field diameter 86
- **5.4** Waveguide dispersion in monomode fibers 88
- **5.5** Waveguide and material dispersion in monomode fibers 90
- **5.6** Dispersion-shifted and dispersion-flattened fibers 92
  - References 94
  - Problems 95

6 **Propagation of light rays in multimode graded index fibers** 96

- **6.1** The eikonal equation 97
- **6.2** Solutions of the eikonal equation for a cylindrical symmetrical fiber and the resulting ray equations 99
- **6.3** Some analytical solutions 101
- **6.4** Numerical solutions 109
- **6.5** Ray congruencies, the h, g-coordinate system 110
- **6.6** The local numerical aperture 114
- **6.7** The relationship between ray congruencies and modes 115
- **6.8** The WKB method 117
  - References 119
  - Problems 119

7 **Dispersion in graded index fibers** 121

- **7.1** Mode model 122
- **7.2** Ray model 129
  - References 135
  - Problems 135

8 **Light sources and detectors** 137

- **8.1** Choosing the wavelength region 137
8.2 The light-emitting diode (LED)  
8.3 The semiconductor laser diode (LD)  
8.4 Semiconductor laser versus LED  
8.5 Photodiodes  
References  
Problems  

9 Modulation of semiconductor light sources  
9.1 The rate equations  
9.2 The laser condition  
9.3 The efficiency of lasers  
9.4 The turn-on delay of a laser and the behaviour of an LED  
9.5 Transient behaviour of a laser  
9.6 Modulation of a laser by small signals  
9.7 Amplitude noise of lasers  
References  
Problems  

10 Transfer characteristic and impulse response of fiber communication systems  
10.1 Transmission via a single-mode fiber  
10.2 Transmission via multimode fibers  
References  
Problems  

11 Power launching and coupling efficiency  
11.1 The ray density of a Lambertian source in the phase space  
11.2 Power launching from the source into a multimode fiber  
11.3 Multimode fiber–fiber coupling  
11.4 Coupling model for single-mode fibers  
11.5 Power coupling from the source into single-mode fibers  
11.6 Single-mode fiber–fiber coupling  
11.7 Fiber–detector coupling  
References  
Problems  

12 Receiver principles and signal-to-noise ratio in analog receivers  
12.1 Connection diagram and equivalent scheme of photodetectors  
12.2 The impulse response of a PIN photodiode  
12.3 Signal-to-noise ratio in analog receivers
Contents

12.4 The thermal noise in front-end amplifiers 273
References 280
Problems 280

13 Receivers for digital optical fiber communication systems 283
13.1 Introduction 283
13.2 Analysis of the simplified receiver model 284
13.3 The quantum limit 289
13.4 The general receiver model 290
References 302
Problems 302

14 System noise 304
14.1 Intensity noise of the light source 305
14.2 Competition noise 306
14.3 Partition noise 306
14.4 Modal noise 312
14.5 The signal-to-noise ratio due to system noise and receiver noise 320
References 322
Problems 322

15 System components and aspects of system design 324
15.1 Introduction 324
15.2 Comparison of optical fibers and copper cables 325
15.3 Optical fiber cables 326
15.4 Splices and connectors 328
15.5 Optical isolators 333
15.6 Polarization-maintaining fiber 334
15.7 Wavelength multiplexing 336
15.8 Repeater distance and link budget 341
15.9 Line coding 344
15.10 Selection of the system components 348
References 350

16 Coherent optical fiber communication 351
16.1 Introduction 351
16.2 Basic principles of coherent optical systems 352
16.3 Signal-to-noise ratio of coherent optical receivers 356
16.4 Balanced mixing and phase diversity reception 358
16.5 Polarization aspects of coherent systems 365
16.6 Concluding remarks

References

Appendix 1 Bessel functions

Appendix 2 Transmission of modulated signals via bandpass systems

Appendix 3 The propagation of Gaussian beams in free space and optical systems

Appendix 4 Poisson processes

Appendix 5 Some physical constants

Index
Preface

Since the early 1970s, the authors of this book have given courses in optical glassfiber communications at the Department of Electrical Engineering of the Eindhoven University of Technology, as a part of their general teaching activities in telecommunications. Over the years they have selected topics that, on the one hand, give a good overview of the main principles of optical fiber communications and, on the other hand, are well suited to being taught in the classroom. This book is a compilation of the class notes originally established by the authors and updated by continuing use. It assumes some basic knowledge of the principles of electromagnetic fields, optics, semiconductor physics, Fourier analysis and noise calculations. Chapters 1, 2, 6, 7, 8, Sections 12.1–12.3 and 13.1–13.3 and Chapter 15 contain material for an undergraduate course, while the rest of the book can be taught in a graduate course. In addition, the text is well suited as a reference for scientists and engineers in research and development laboratories.

Chapter 1 starts with a comparison of optical communication systems with other communication systems of different kinds. Attention is paid to the fabrication processes that are used to produce glassfibers, to the different causes of attenuation and to a method to measure this attenuation. The most important properties of the light sources and the detectors, the elements necessary to form a simple communication link with an optical waveguide as the transmission medium, are reviewed and a general model of a link is established. The first part of the book, Chapters 2–7, deals with the propagation of light through optical waveguides. Chapter 2 starts with the treatment of slab waveguides, on the one hand as an introduction to the solution techniques used in subsequent chapters and on the other hand because these waveguides play an important role in integrated optics. The waveguides are analyzed with the help of Maxwell’s equations, the characteristic equation with its discrete solutions is derived and the mode concept is introduced. In Chapter 3 this is repeated for the round step index waveguide. The E, H and hybrid modes are derived and attention is paid to LP modes. The expressions for the phase characteristics that follow from the solutions are further developed in Chapter 4, which treats the dispersion of the waveguides and the influence of the fiber on the bandwidth. A separate chapter, Chapter 5, is devoted to single-mode fibers. The principles derived in the earlier chapters are applied for this special case. Chapter 6 treats graded index fibers. In the previous chapters the wave optics model was used. In this chapter the waveguides are analyzed with the geometric optics model, using the eikonal equation as the starting point. At the end of the chapter the results are compared with the results obtained by the WKB method. In Chapter 7 two
different models are used to derive the dispersion in graded index fibers. Chapter 8 deals with the semiconductor light sources and detectors that are used in optical fiber communication systems. Little attention is paid to the physical background, the emphasis being on the external characteristics. This approach is further elaborated in Chapter 9 for the modulation aspects of the sources. Once the optical fiber waveguiding and the light sources and detectors are introduced, a description of an entire link can be given; this is done in Chapter 10. A great deal of the total link loss is due to coupling losses; Chapter 11 gives an extensive treatment of these coupling losses, both in multimode and single-mode fiber links. The receivers in an optical transmission system require special attention. Noise phenomena are quite different compared to the classical communication model, where the noise is assumed to be additive, stationary and Gaussian. The shot noise, or Poisson noise, does not show these elegant properties. That is why analog receivers (Chapter 12) require a different approach compared to digital receivers (Chapter 13). Apart from the aforementioned shot noise, multimode optical fiber systems can suffer from system noise (Chapter 14), which arises from non-ideal matching of system components. In general, realization of an optical fiber link or network requires more components than standard optical fiber, light source(s) and detector(s). Such components may be: wavelength division multiplexers, optical isolators, polarization-maintaining fibers, etc. These components and other system aspects are treated in Chapter 15. Finally, Chapter 16 has been devoted to coherent optical fiber communication, a subject to which much attention is now being paid in laboratories and which may lead to very promising applications in the future.

A number of subjects closely related to optical fiber communications, but not specific to it, are dealt with in the appendices. These include: Bessel functions, transmission via bandpass systems, Gaussian beams and Poisson processes.

At the end of most of the chapters some exercises are provided, giving the reader the opportunity to check his or her knowledge by means of practical problems.

A task as extensive as writing a book always requires support. We thank Dr Peter Attwood for correcting the English text, and Gerard Baten for producing a number of the figures. One of the authors (W. v. E.) thanks his wife Kitty for typing his part of the manuscript.