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Optical Communication Systems

JOHN GOWAR

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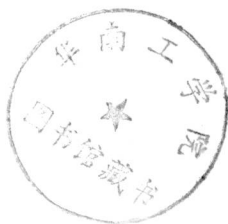
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OPTICAL COMMUNICATION SYSTEMS

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Foreword

With the appearance of this second volume in Prentice-Hall's new series on optoelectronics, a few words of editorial comment seem appropriate. The accent of the series will be on texts written with an eye to teaching rather than as monographs intended primarily for research workers already well versed in the general principles of their subject. A series on optoelectronics seems especially timely in view of the rapid expansion of interest in this subject. This expansion is being driven primarily by the burgeoning developments in a variety of applications fields, especially in electronic communications. In the past few years it has become widely recognized that the rapidly growing need for high speed, high information capacity communications systems will strain the capacity of traditional techniques involving all-electrical networks. These needs, driven particularly by the widespread introduction of links between computers and also by the desire to distribute video information over complex networks, have validated the requirement for optical communication techniques. Conveniently, such optical communication systems are just emerging from the status of laboratory prototypes mainly developed in the 1970s. A variety of Government-supported schemes have recently been launched in the UK to assist in the introduction of these new methods in the communications industry. Foremost are the JOERS and the Alvey schemes, both of which include the promotion of optoelectronic research and development work between industry and government, university or technical college R&D groups. These initiatives will appreciably increase the already strong demand for personnel trained in optoelectronics. Development of a more general awareness of the subject amongst technically trained people, and even for the general public, will also become increasingly appropriate.

The first book in the Prentice-Hall Optoelectronics series, by John Wilson and John Hawkes, was published in Spring 1983. It is a general text, set at a level appropriate for a final year undergraduate course on the basic principles of the three areas into which the subject can conveniently be divided. These three elements are optical (often called lightwave) communications, optical signal processing, and displays. This second text in the series, by John Gowar, treats the first of these elements, the core topic for the majority of those

interested in the subject, in significantly greater depth. Starting with basic concepts, the reader is taken to a stage appropriate for an MSc degree examination course. Both texts emphasize their basically tutorial approach by the inclusion of many useful examples in every chapter. Gower also ends each chapter with a concise summary of the basic principles which have been illustrated. I believe that these texts, taken in combination, will enable a student in science and engineering to build up a fully comprehensive appreciation of optical communications. Both texts provide ample references to original research publications for those requiring detail on specific aspects.

Further volumes in the series are in preparation or are being planned to treat other aspects of optoelectronics in comparable detail. A number of texts will also cover specific areas of specialization in rather greater depth.

*P. J. Dean
Series Editor
October 1983*

Preface

It has come to be generally accepted that during the last two decades of the 20th century optical fiber communication techniques will become firmly established in most of the developed countries of the world. It follows that during this period the emphasis in the teaching of the principles of telecommunications and data transmission will move from being concerned entirely with electrical and radio systems to dealing with optical, electrical and radio techniques on more or less equal terms.

Up to now the subjects associated with optical communications have been discussed mainly in review articles and in advanced, usually multi-author, specialist texts. One or two books set at a much simpler technical level and aimed at the nonspecialist user of optical fiber technology have also appeared. Many of these are excellent, but their main purpose has been to review the subject rather than to teach it. The present book is intended to be a general tutorial introduction set at a level suitable for final-year undergraduate students of Electronic Engineering, Physics or other related subjects. It is hoped that it may equally meet the needs of graduate engineers and scientists who are contemplating research or development work in this field or who have a general interest and seek a comprehensive introduction. To a large extent the book has been developed from a third-year undergraduate course given for several years by the author to Electrical and Electronic Engineering and Physics students in the University of Bristol.

One of the nice features of a new technology is the way it brings together in common interest people with widely varying academic backgrounds, and cuts across existing, artificial subject boundaries. However, this also gives rise to one of the biggest problems in a book of this kind, and that is the level of prior knowledge to assume in each of the traditional subject areas covered. Here, a basic knowledge of electromagnetic theory and of solid-state physics is assumed, as is some familiarity with the elementary theory of analogue and digital communications systems and electronic circuits. Naturally, the level of approach will reflect the inclination and interest of the author. What has to be avoided, though, is making the treatment of subjects with which the reader is

familiar appear trivial (or worse, misguided!) without rendering them unintelligible for the reader with only a limited background. Time will tell to what extent these traps have been avoided.

It may be noticed that, unlike most books concerned in some way with electromagnetic waves, no attempt has been made here to derive, justify or explain Maxwell's equations. There seemed to be nothing that could usefully be added to the enormous literature which already exists on this subject. On the other hand, consideration of semiconductor properties has been developed here from a fairly basic level in the hope that some readers may find helpful the largely diagrammatic approach based on electron energy levels.

The end-of-chapter references have deliberately been kept small in number and are intended to serve two purposes. Some are sources of material, knowledge of which is assumed in the text. Others extend the subject beyond the level of the treatment given here. It must be emphasized that this book is not intended to be a review of current research activity and no attempt has been made to reference the enormous literature. Several other texts provide a ready access to this, and in particular the 1980 review paper of Botez and Herskowitz* contains no fewer than 640 references. The October 1980 issue of *Proceedings of the I.E.E.E.* and the July 1978 issue of *I.E.E.E. Transactions on Communications* are both special issues devoted to optical fiber systems and give a good review of the progress and activities in the subject at those dates.

The present text has benefitted greatly from the comments and suggestions made by the reviewers, and the author has been grateful for them. The many remaining deficiencies are, of course, his own responsibility. Thanks must go to many past and present colleagues whose influences have helped in various direct and indirect ways. Special thanks are due to Geoff Reed and Ted Thomas for giving up their time to read and criticize drafts of the manuscript, and most particularly to Angela Tyler for typing the manuscript, some parts many times!

J. Gowar
University of Bristol
October 1983

* D. Botez and G. J. Herskowitz, Components for Optical Communications Systems: A Review, *Proc. I.E.E.E.* **68** (6) 689-731 (1980).

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A General Introductory Discussion

1.1 HISTORICAL PERSPECTIVE

There is, of course, nothing new in the use of optical frequencies for the transmission of information. Visual methods of communicating are widely used in the animal kingdom, obvious examples being courtship displays and warnings of aggressive intent, and from the time of the most primitive human civilizations man has employed artificial optical techniques to send information over long distances. He has, for example, used smoke signals or reflected sunlight during the day and fire beacons at night. Perhaps we may indulge briefly in two references from classical antiquity:

In Aeschylus's play *Agamemnon*, written in the 5th century B.C. and concerned with events from mythical times nearly a millennium earlier, Clytemnestra explains how she had learned of the fall of Troy the previous night:

'Hephaistos the fire-god, beaoning the news,
Flashed a courier-chain of fires from peak-to-peak.'[†]

She then gives a graphic description of the eight stages used to relay the news by beacon from Asia Minor to Argos.

More prosaically, but possibly more reliably, Herodotus writing a little later tells how in 480 B.C. the Persian leader Mardonius dreamed of sending a similar message by similar means in the other direction across the Aegean, to inform his emperor (Xerxes) of the fall of Athens. His dream was unfulfilled.

Each of these examples is concerned with the transmission of a single item of information by means of a prearranged signal. Although more sophisticated methods of signalling were discussed in classical times, only the use of beacons

[†] Line 281 of the *Oresteia*. In the translation by Frederick Raphael and Kenneth McLeish: *The Serpent Son*, C.U.P. (1979).

seems to have continued over the intervening centuries until the development of the semaphore towards the end of the 18th century. In due time this was overtaken by the electric telegraph on land and had to compete with signalling flags and shuttered signalling lamps at sea. Such techniques were in turn largely replaced by the telephone and by wireless telegraphy. At this point a major change took place in the form in which information was transmitted. The early systems were all what we would now call *digital* systems, but the telephone and 'radio' have allowed the transmission of *analogue* information in analogue form, that is as a continuous time-varying electrical waveform.

It is clear that as we enter the 21st century, the era of 'information technology', telecommunication will again revert to an optical frequency carrier and will be predominantly digital in form. It is true that some specialist users may wish to preserve analogue transmission and some to use unguided waves in the atmosphere or in space, but it may confidently be predicted that most information will be transmitted as a sequential stream of light pulses guided along silica optical fibers, the pulses representing binary digital data. It is with the techniques that are being used in the first generation of such systems, and the limitations that are imposed on them, that this book is concerned. The technology and techniques to be described are all well established; nothing new needs to be invented for the wholesale introduction of silica fibers (rather than copper cable) as the principal medium of transmission. Legitimate delays in making this change arise from the need to establish the reliability and life of components and to define suitable standards, but the country which fails to invest in an adequate telecommunication system will be left behind in an age in which the electronic storage, processing and transmission of information will be one of the main activities of business life.

The novelty of modern optical communication systems is that the optical signal is usually guided and the signalling rates are very high. But it needs to be stressed that they are, as yet, no higher than those used in modern, electronic, digital, trunk-telephone equipment. The main incentive for changing from coaxial cable and microwave radio to optical fiber is that of minimizing the overall system cost. It is, therefore, essential that the information capacity of fibers is used to the maximum and that the signalling rates employed should be able to match those of alternative electrical and radio channels. The interest concerns optical pulse repetition frequencies in the range 1 M^+ 1000 Mb/s. It has been established, as we shall see later, that the spacing between the repeaters of an optical system can be made sufficiently large for most to be sited in existing telephone exchange buildings. The need for remote, underground repeaters with their associated problems of power supply and maintenance is then largely eliminated. Further advantage derives from the small size, the overall compatibility, and the relative simplicity of the fiber system. The main bulk material, silica, is more abundant and should be cheaper than the copper needed for guided electrical systems.

The modern era of optical communication may be said to have originated with the invention of the laser in 1958, and the first developments soon followed the realization of the first lasers in 1961. Compared to conventional sources of optical frequency, laser radiation is highly monochromatic and coherent, and very intense. In fact it is much more like the radiation generated by a normal microwave transmitter. It is thus a natural step to think of its potential as a carrier for telecommunications. Initially the principal motivation was the enormous bandwidth that would be available, if it were possible to modulate the laser light at only a few percent of its fundamental frequency. The importance of this will be familiar to most readers and is further discussed in Section 1.2. We find that in a system using a helium–neon laser (free space wavelength $0.63\text{ }\mu\text{m}$, frequency $4.7 \times 10^{14}\text{ Hz}$) a channel bandwidth of 1% of the laser frequency would be 4700 GHz—enough to carry nearly a million simultaneous television channels! The frequencies and wavelengths corresponding to the radio, microwave and optical regions of the electromagnetic spectrum are illustrated in Fig. 1.1. It should be noted that a logarithmic scale has been used. This means that each decade of frequency represents a range, or bandwidth, nine times greater than the whole range of frequencies below it.

The 1960s saw many ideas for laser transmitters using different modulation techniques (frequency modulation, phase modulation, intensity modulation, amplitude modulation, polarization modulation, pulse frequency modulation) and a number of systems using unguided transmission in free space were developed. Some of these will be discussed further in Chapter 16.

During this period a number of people experimented with guided systems in which the laser beam was confined to a transmission channel by lenses spaced at 10 m or 100 m intervals. It is to the credit of K. C. Kao and his fellow workers at the Standard Telecommunications Laboratories in Harlow, England, who were active in this work, that they came to realize that a much simpler guidance system, using a continuous glass fiber of a kind that had already been employed in short lengths for endoscopes and other applications, might be used for telecommunication. The 1966 paper by Kao and Hockham

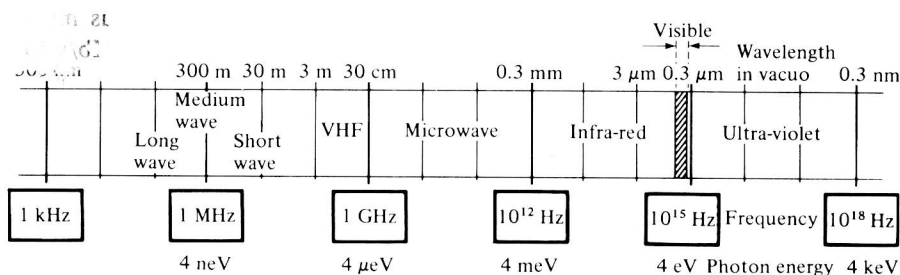


Fig. 1.1 The electromagnetic spectrum.