Optical Communications

SECOND EDITION

Robert M. Gagliardi
Sherman Karp

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Second Edition

Robert M. Gagliardi
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PREFACE

This second edition is an updated version of our earlier text published in 1976. Much of the mathematical modeling and statistical analysis that was detailed in that first edition has been significantly reduced, so as to be more compatible with modern analysis. We have focused on those specific optical technologies that have emerged since that first book. In addition we have inserted new material in the key areas of digital communications, fiberoptics, lightwave networks, atmospheric channels, and space links, all of which are now critical topics in optical applications. We have also inserted brief sections on optical hardware and device descriptions to make the text somewhat self-contained, and to bridge the gap between the theory emphasized in the first edition and the applied analysis emphasized here. We have again chosen to integrate both fiber and space optics in our presentation which, we feel, separates the book from the many recent optics books that concentrate solely on fiber components and fiber communications.

The objective of the new edition remains the same as that of the first — to emphasize the system aspects of optical communications, as opposed to detailed hardware and device description. A reader familiar with our first edition will find that although much of the earlier analytical procedures are still applicable, the present edition is more streamlined and oriented toward modern analysis and design. The material is again presented in a textbook format with a completely new set of homework problems and references to aid the instructor or self-learning reader. The book is aimed at several specific types of readers — the student in electrical engineering or electrophysics, the communication engineer who may wish to become familiar with the potential of optics, and the optical engineer who perhaps has not considered all the theoretical implications of optical information transmission. We consider the text appropriate for a one or two semester course in optical communications at a senior or graduate level. At USC the text is used in an optical communication course complementing undergraduate and graduate companion courses on optics and devices.

Chapter 1 introduces the optical system, defining applications and terminology, and setting the framework for the remaining chapters. A review of optical fields, sources, channels, and signal descriptions are introduced to prepare the reader. Chapter 2 explores optical field reception, field focusing, and optical filtering. The objective is to lead the reader through the necessary analysis to determine power levels in both fiber and space systems.

Chapter 3 is perhaps the most important chapter, since it covers the conversion of optical fields to electronic current flow via photodetection. To the communication engineer, it is here that the important statistical models of the receiver are generated for evaluating system performance in later chapters. Although the topic extended over three chapters in the first edition (photon counting, shot noise theory, and photodetection) it has been consolidated into a single chapter here, de-emphasizing the counting statistics while establishing useable photodetection models. New material on photomultiplication has been inserted.

The next chapters begin the application to system design, and divide naturally into two separate chapters. Direct detection (noncoherent) systems are covered in Chapter 4, and heterodyne (coherent) systems in Chapter 5. The material is presented in the language of the communication engineer, emphasizing demodulation, signal to noise ratios, and performance evaluation. Much of this involves new and updated material of the same topics covered in the first edition.

Chapter 6 specializes to digital communications and data bit transmission, an important area in modern systems. We focus on the important digital formats that have evolved over the last decades, with newer material inserted in the areas of bit error probabilities, coding, and digital clocking. Chapter 7 confines analysis to the fiber optic channel, in which earlier fiber power flow analysis is combined with modulation and signalling to define the overall communication link.

Chapter 8 extends the individual fiber link into combined links forming lightwave networks. This area, which was not covered in our first edition, has progressed rapidly, especially with today's emphasis on lightwave information highways and cable distribution systems. The basics of light distribution, switching, and multiple accessing are presented.

Chapter 9 is devoted entirely to atmospheric optical propagation, and its effect on communication performance in space links. The objective is to guide the communication engineer through available data and graphs to assess the channel effects on link performance. Chapter 10 applies to satellite and space vehicle communications using laser beams to establish crosslinks. Beam pointing, beam acquisition, and beam tracking are discussed and related to the overall link performance. Since beam tracking is generally integrated directly into the communication link, the performance of each is directly interrelated through their individual parameters. This interrelationship is developed in this chapter.

We wish to thank Ms. Milly Montenegro, Ms. Rohini Montenegro, and the staff of the Communication Science Institute at USC for their help in preparing the new edition. In addition, we would like to thank the various practicing

engineers and scientists, classroom students, and university instructors for their comments and suggestions on the first edition that aided us in upgrading to this edition.

Robert M. Gagliardi
Sherman Karp

Conversion Formulas

PHYSICAL CONSTANTS

Speed of light, c	=	2.998×10^{8} m/sec
Electron charge, e	=	1.601×10^{-19} C
Planck's constant, h	=	6.624×10^{-34} W-sec/Hz = (-335.4 dBW/Hz^2)
Boltzman's constant, k	=	1.379×10^{-23} W/°K-Hz

CONVERSION FACTORS

1 micron = 10^{-6} meters = 10^{-4} cm
1 Å = 10^{-4} microns = 10^{-10} meters
1 arc sec = 2.78×10^{-4} degrees = 4.89×10^{-6} radians
Frequency in Hz = 3×10^{14}/wavelength in microns
Bandwidth in Hz at center wavelength $\lambda = (c/\lambda^2)$ [bandwidth in wavelength]

OPTICAL FREQUENCIES AND WAVELENGTHS

Violet	≈	7×10^{14} Hz	0.38–0.48 microns
Blue	≈	6×10^{14} Hz	0.48–0.52 microns
Green	≈	5.6×10^{14} Hz	0.52–0.56 microns
Yellow	≈	5.1×10^{14} Hz	0.56–0.62 microns
Orange	≈	4.8×10^{14} Hz	0.62–0.64 microns
Red	≈	4.4×10^{14} Hz	0.64–0.72 microns
Infrared	≈	3×10^{14} Hz	0.7–100 microns

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1

THE OPTICAL COMMUNICATION SYSTEM

The objective of any communication system is the transfer of information from one point to another. This information transfer is accomplished most often by superimposing (modulating) the information onto an electromagnetic wave (carrier). The modulated carrier is then transmitted (propagated) to the destination, where the electromagnetic wave is received and the information recovered (demodulated). Such systems are often designated by the location of the carrier frequency in the electromagnetic spectrum (Fig. 1.1). In radio systems, the electromagnetic carrier wave is selected with a frequency from the radio frequency (RF) portion of the spectrum. Microwave or millimeter systems have carrier frequencies from those portions of the spectrum. In an optical communication system, the carrier is selected from the optical region, which includes the infrared, visible, and ultraviolet frequencies.

The principal advantages in communicating at optical frequencies are (1) the potential increase in modulation bandwidth, (2) the ability to concentrate power in extremely narrow beams, and (3) the significant reduction in component sizes. In any communication system, the amount of information transmitted is directly related to the bandwidth (frequency extent) of the modulated carrier, which is generally limited to a fixed portion of the carrier frequency itself. Thus, increasing the carrier frequency theoretically increases the available transmission bandwidth, and therefore the information capacity of the overall system. This means frequencies in the optical range will have a usable bandwidth approximately 10^5 times that of a carrier in the RF range. This available improvement is extremely inviting to a communication engineer vitally concerned with transmitting large amounts of information. In addition, the ability to concentrate available transmitter power within the transmitted electromagnetic wave also increases with carrier frequency. Thus, using higher carrier frequencies increases the capability of the system to achieve higher power densities, which generally leads to improved performance. Lastly, operation at the extremely small wavelengths of optics produces system devices

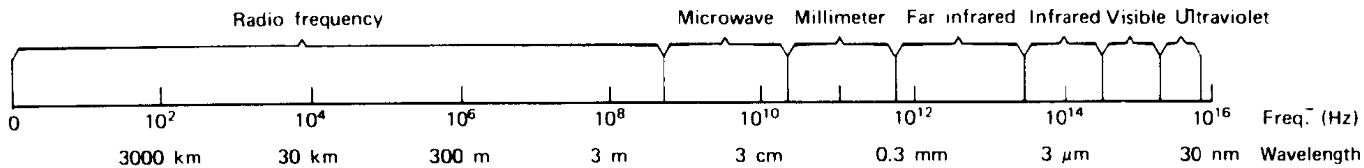


Figure 1.1. The electromagnetic spectrum.

and components that are much smaller than their equivalent electronic counterparts. For these reasons, optical communication has emerged as a field of special technological interest.

Communicating at optical frequencies has several major differences from RF communications. Because optical frequencies are accompanied by extremely small wavelengths, optical component design requires essentially its own technology, completely different from design techniques associated with RF, microwave, and millimeter devices. As a result, optical devices, although emulating equivalent electronic devices, may have performance characteristics significantly different from their electronic counterparts.

Another drawback to optical communications is the detrimental effect of the propagation path on the optical carrier wave. This is because optical wavelengths are commensurate with molecule and particle sizes, and propagation effects are generated that are uncommon to radio and microwave frequencies. Furthermore, these effects tend to be stochastic and time varying in nature, which hinders accurate propagation modeling. A vast amount of experimental data has been collected to aid in understanding this optical propagation phenomenon and, although certain models have been established, continued exploration is required for refinement and further justification.

The development of optical components and the derivation of propagation models, however, are only part of the overall system design. A communication engineer must also be concerned with the choice of components, the selection of system operations, and finally the interfacing or interconnecting of these operations in the best possible manner. These interfacing decisions require reasonably accurate mathematical models, which indicate component performance, anomalies, and degradations, knowledge of which can be used to advantage in system design. It is this aspect of optical communications that this book attempts to elucidate. Our objective is to understand system capability and to formulate system-design procedures and performance characteristics for the implementation of an overall optical communication system.

1.1 OPTICAL SYSTEMS

The block diagram of a generic optical communication system is shown in Figure 1.2. The diagram is composed of standard communication blocks, which are endemic to any communication system. A source producing some type of information (waveforms in time, digital systems, etc.) is to be transmitted to some remote destination. This source has its output modulated onto an optical carrier (a carrier frequency in the optical portion of the electromagnetic spectrum). This carrier is then transmitted as an optical light field, or beam, through the optical channel (free space, turbulent atmosphere, fiberoptic waveguide, etc.). At the receiver, the field is optically collected and processed (photodetected), generally in the presence of noise interference, signal distortion, and inherent background radiation (undesired light fields or other

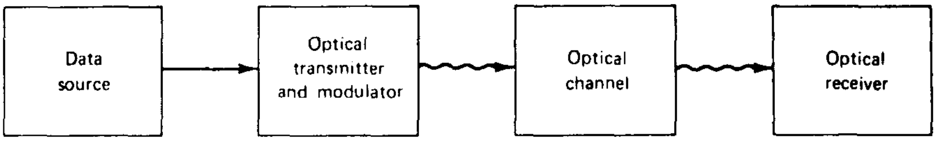


Figure 1.2. Optical communication system block diagram.

electromagnetic radiation). Of course, except for the fact that the transmission is accomplished in the optical range of carrier frequencies, the operations just mentioned describe any communication system using modulated carriers. Nevertheless, the optical system employs devices somewhat uncommon to the standard components of the RF system. These devices have significant differences in their operation and associated characteristics, often requiring variations in design procedures.

The modulation of the source information onto the optical carrier can be in the form of frequency modulation (FM), phase modulation (PM), or possibly amplitude modulation (AM), each of which can be theoretically implemented at any carrier frequency in the electromagnetic range [1]. In addition, however, several other less conventional modulation schemes are also often utilized with optical sources. These include intensity modulation (IM), in which information is used to modulate the intensity (to be defined subsequently) of the optical carrier, and polarization modulation (PLM), in which spatial characteristics of the optical field are modulated.

The optical receiver in Figure 1.2 collects the incident optical field and processes it to recover the transmitted information. A typical optical receiver can be represented by the three basic blocks shown in Figure 1.3, consisting of an optical receiving front end (usually containing some form of lens or focusing hardware), an optical photodetector, and a postdetection processor. The lens system filters and focuses the received field onto the photodetector, where the optical signal is converted to an electronic signal. The processor performs the necessary amplification, signal processing, and filtering operations to recover the desired information from the detector output.

Optical receivers can be divided into two basic types: power detecting receivers and heterodyning receivers. Power detecting receivers (often called direct detection, or noncoherent, receivers) have the front end system shown in Figure 1.4*a*. The lens system and photodetector operate to detect the instantaneous power in the collected field as it arrives at the receiver. Such receivers represent the simplest type for implementation and can be used whenever the transmitted information occurs in the power variation of the received field.

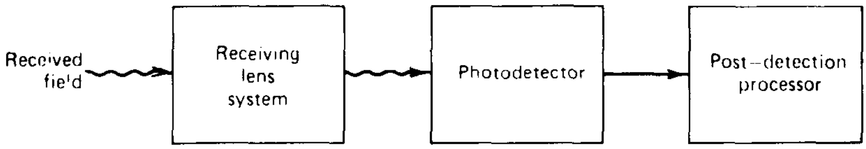
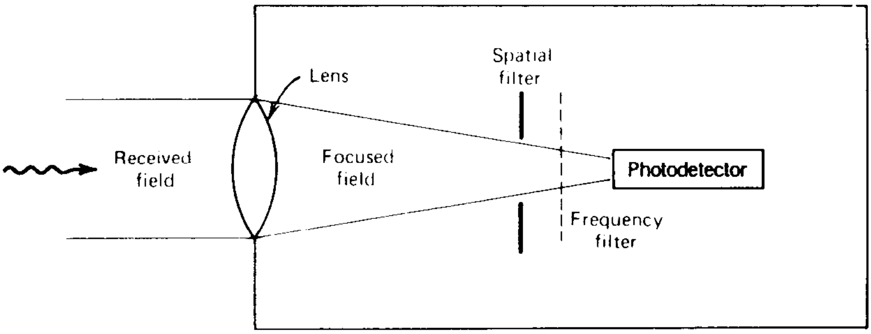
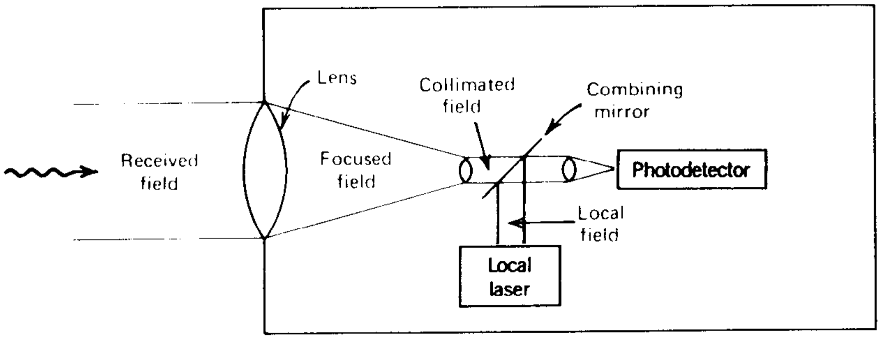


Figure 1.3. The optical receiver.



(a)



(b)

Figure 1.4. (a) Direct detection receiver. (b) Heterodyne detection receiver.

Heterodyning receivers have the front end system shown in Figure 1.4*b*. A locally generated lightwave field is optically mixed with the received field through a front end mirror, and the combined wave is photodetected. Such receivers are used whenever information is amplitude modulated, frequency modulated, or phase modulated onto the optical carrier. Heterodyning receivers are more difficult to implement and require close tolerances on the spatial coherence of the two optical fields being mixed. For this reason, heterodyned receivers are often called (spatially) coherent receivers. For either type of receiver, the front end lens system has the role of focusing the received or mixed field onto the photodetector surface. This focusing allows the photodetector area to be much smaller than that of the receiving lens.

The receiver front end, in addition to focusing the optical field onto the photodetector, also provides some degree of filtering, as shown in Figure 1.4. These filters are employed prior to photodetection to reduce the amount of undesired background radiation. Optical filters may operate on the spatial properties of the focused fields (polarization filters, field stops, etc.) or may filter in the frequency domain; that is, they pass certain bands of frequencies

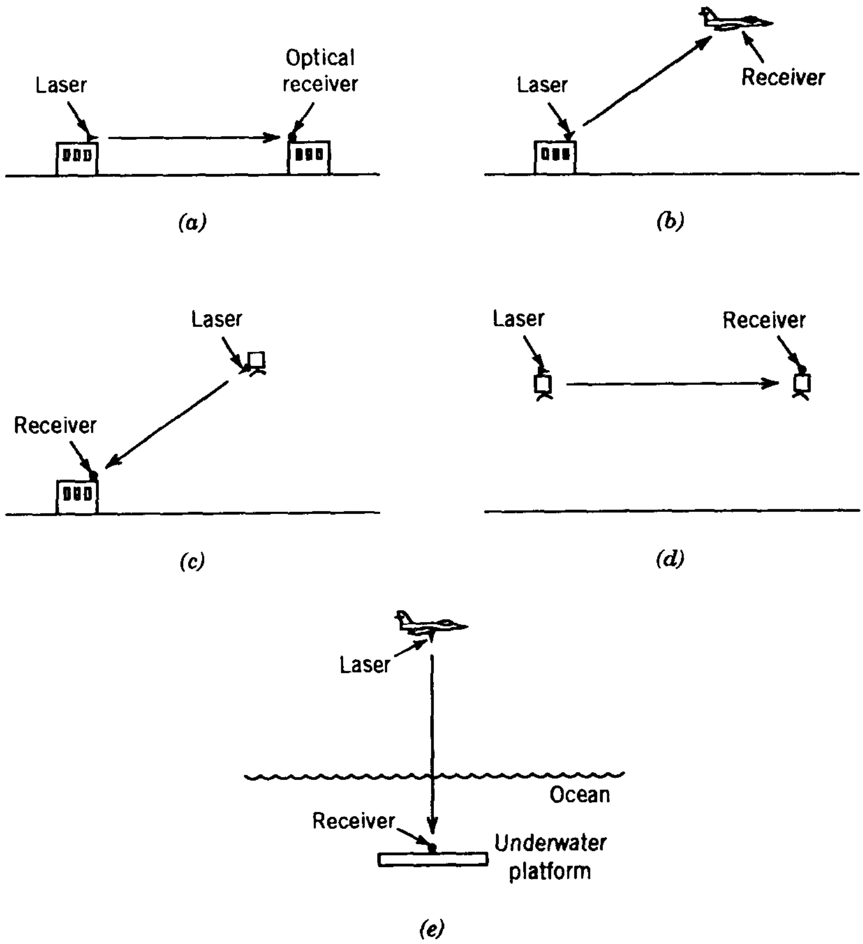


Figure 1.5. Optical space links. (*a*) Terrestrial, (*b*) ground based to air, (*c*) spaced based to ground, (*d*) intersatellite, (*e*) air to underwater.

and reject others. The latter filters determine the bandwidth of the resulting optical field subsequently photodetected.

Photodetectors convert the focused optical field into an electrical signal for processing. Although there are several types of detectors available, all behave according to quantum mechanical principles, utilizing photosensitive materials to produce current or voltage responses to changes in impinging optical field power. The basic model defining this interaction for all photodetectors is well accepted, although detectors may differ in their output response characteristics. This basic model, which is examined in detail in Chapter 3, is extremely important to the communication engineer because it generates the inherent statistics that must be utilized in design of the postdetection processing. The most common type of photodetectors are the phototubes, photodiodes, and photomultipliers.

The detection of optical fields is hampered by the various noise sources