ELECTRO-OPTICS

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PREFACE

Electro-optic devices and concepts are becoming more important, with increasing application in industry, government, and consumer-related areas. The ability to work with and understand the various electro-optic devices and systems is a skill that is required for many active professionals in engineering and related disciplines. There is a strong need for an undergraduate-level elective in electro-optics that provides an introduction to the fundamental principles. Currently, professionals who work in electro-optics must rely on experience, tutoring by colleagues, or extraction of information from a variety of widely scattered and incompatible references. Of the available reference books that deal with electro-optics, none is suitable for use as a textbook in a course that teaches fundamentals and includes problems to provide knowledge of practical analysis methods and state-of-the-art parameter values.

The primary objective for this book is to serve as a practical textbook in the areas of electro-optics that are fundamental to a wide range of applications. It is not intended to cover in detail such specialty areas as fiber optics, holography, and optical communications, which are covered in a number of specialized textbooks. This book is suitable for use in a one- or two-semester sequence at the advanced undergraduate level or in a first-level introductory graduate course.

Students using this book are assumed to have a fundamental knowledge of integral calculus and linear systems theory. An understanding of Fourier analysis methods is assumed; however, a review of appendix A will provide necessary background for those students who need it. Although not essential, an understanding of electromagnetic field theory is useful for the material on coherent optical data processing, and a basic course in electronics and semiconductor theory is helpful for understanding the material on optical detectors.

This book makes no attempt to cover in detail all the topics that are considered to be a part of electro-optics. To do so would require that multiple volumes be produced and would require contributions from several authors. The book does attempt to provide a sound basis for analyzing a large number of electro-optical systems. Beyond that, the material covered is of necessity biased by my experience and past research activities. In particular, there is a bias toward the analysis of electro-optical sensors and the characterization of the optical properties of the atmosphere.

The organization of the book is such that fundamental material is presented in the early chapters, with more specialized applications presented in the later chapters. A one-semester course cannot cover all the material in the book. One way of covering the basics in one semester is to present chapters 1 through 6 and some material from one or two other chapters. A second course could cover the remaining specialty areas in the text and some supplementary material.

As with all authors, I am indebted to a number of people who have played a key role in bringing this book to fruition. In particular, I am indebted to Bob Eisele and Hal Henry, who taught me most of what I know about electro-optical sensors. Professor Martial Honnell taught me how to evaluate optical systems in a practical way. My editor, Merrill Floyd, understands what deadlines actually mean. My good friend and colleague Richard Wiener persuaded me to quit planning to write a book and to actually do it. Several colleagues at the Army Missile Command in Huntsville, Alabama provided opportunities to help solve interesting problems in electro-optics; they contributed indirectly to the content of this book. I wish to thank my reviewers for their many helpful comments. In particular, Jack Gaskill made suggestions that I hope have resulted in a more clear presentation of several concepts. Many others have offered encouragement and I thank them all. Several of my colleagues will see ideas here that they have helped to shape; however, the interpretation is mine and all responsibility for errors or misinterpretation is solely mine.

A particular debt goes to my sons Sean and Kelly, who have forgone weekend ski trips and other activities while this book was being written. And a special note of gratitude goes to my wife, Judy, who has put up with the noise from my printer and has given me her full support in this effort. The encouragement of my father and stepmother has helped me through some rough spots.

As a final note, the book was prepared on an Apple computer using the word processor Gutenberg from Micromation, Inc. of Ontario, Canada. This word processor has fantastic capability for preparing scientific manuscipts and the many hours I spent learning how to use it were well worthwhile.

CONTENTS

CHAPTER 1

INTRODUCTION TO ELECTRO-OPTICS

The purpose of this textbook is to present material that is fundamental to all of the related areas of electro-optics and to introduce a number of specialty areas of electro-optics. Several of the topics included in this book are included under the general headings of optoelectronics and optics. The differences between these fields and electro-optics is not distinct, nor is it always clear that particular topics fit naturally under one or another heading.

This book brings together material on topics that are fundamental to electro-optics and includes material on specific electro-optics applications. Some of this material can be found in other references or in textbooks devoted to a single specialty area. For example, there are numerous books available on holography, fiber optics, and optical communications.

This chapter discusses possible definitions for electro-optics and provides a descriptive introduction to selected specialty areas within electro-optics. It ends with a discussion of the organization and content of the remaining chapters.

1.1 ELECTRO-OPTICS

A definition for the term *electro-optics* is given by reference 1 as "the study of the effects of electric fields on optical phenomena." While this definition is desirably simple and correct, it is not indicative of the broad areas of study that have come to be a part of electro-optics. Such diverse applications as electro-optical sensors, optical communication, and optical signal processing are a part of the general area of electro-optics. While the specific methods that are fundamental to these areas are quite different, they all share a common element that may be taken as a definition for electro-optics. This common element is the study of the interaction of matter with the optical spectrum. Interestingly enough, this same phrase has been used as a definition for optoelectronics [2] as well. Optoelectronics has its beginnings in the study of the interaction of semiconductors with optical radiation, such as was observed in light-emitting diodes (LEDs) and phototransistors. The major thrust has been to accomplish electronics functions using optical elements as part of the system. Electro-optics also includes principles that are a part of the more general area of optics. Specifically, concepts that are fundamental to geometric optics and physical optics form the basis for understanding several electro-optics applications. As you can see, the definition of electro-optics has expanded over the past two decades to encompass a more general interpretation than the one given above. So it really is not necessary to define electro-optics, optoelectronics, and optics with precision, nor is it important to classify any particular application as being exclusive to one or the other.

Beyond the preceding comments, this book does not attempt to provide further distinction among the areas of electro-optics, optoelectronics, and optics. Rather, it presents concepts that are fundamental to the study of electro-optics and develops selected specific applications. The use of approximate solution methods and the effect of practical constraints on the theoretical performance of electro-optical systems are illustrated by example analyses and by problems at the end of most chapters. Not all applications areas that can be classified as electro-optics will be presented in detail.

1.2 DANGER — RADIATION

The cover of this book is indeed radiating at the stated level of 1.43×10^{21} photons per second if several assumptions can be made about the surface material. If it is assumed to be a blackbody radiator (emissivity = 1.0) at a nominal room temperature of 300 K, then for the surface area (15×22.5 cm^2), there are approximately 1.43×10^{21} photons emitted every second. An emissivity of unity implies zero reflectance from the surface, which is not quite true. However, if the assumption is modified so that the surface is considered to be a graybody with 50-percent reflectance, the emitted radiation level is reduced by only half. This reduction in emitted radiation is at least partially counterbalanced by photons reflected by the surface from ambient lighting. So within the constraints of the graybody assumption, the total radiation level is approximately as stated.

A blackbody radiator emits photons at all wavelengths (relative number versus wavelength is discussed in detail in chapter 2). The energy of each photon depends on its wavelength and is given by

$$Q_\lambda = h\nu = \frac{hc}{\lambda} \quad \text{(J/photon)} \tag{1.1}$$

where

h = Planck's constant = 6.6252×10^{-34} (J s)

c = speed of light = 3.0×10^{8} (m/s)

λ = wavelength (m)

ν = frequency (Hz)

For example, a photon emitted at a wavelength of 0.5 μm ($\lambda = 0.5 \times 10^{-6}$ m), which corresponds to green light, has energy given approximately as

$$Q_\lambda = 4.0 \times 10^{-19} \quad \text{(J)} \tag{1.2}$$

If the energy per photon is integrated over the distribution of photons versus wavelength for a 300 K blackbody, then the total radiant flux from the book surface is approximately 16 W.

The above example serves two purposes. First it says that radiant flux (or power) can be described in units of watts or in numbers of photons per second. Second, it illustrates the relative magnitudes of energy for a single photon. These radiometric units are defined in chapter 2 and compared with photometric units, which originated with attempts to measure and quantify visible light. Radiometric units are not restricted to visible light wavelengths, and thus form a more sound scientific system of units for evaluating electro-optical devices and systems. Radiometric units are emphasized throughout this book.

1.3 THE OPTICAL SPECTRUM

The electromagnetic spectrum is described in terms of propagating, sinusoidally varying electromagnetic fields, which are characterized by frequency (Hz) or wavelength (m). The relationship between frequency and wavelength is given by

$$v = \nu\lambda \quad \text{(m/s)} \tag{1.3}$$

where

v = velocity (m/s)

ν = frequency (Hz)

λ = wavelength (m)

and, for propagation in a vacuum,

$$v = \nu\lambda = c \approx 3.0 \times 10^{8} \quad \text{(m/s)} \tag{1.4}$$

The ratio of c, the speed of light in a vacuum, to v, the speed of light in any other medium, is defined as the refractive index of that medium. Since v can never

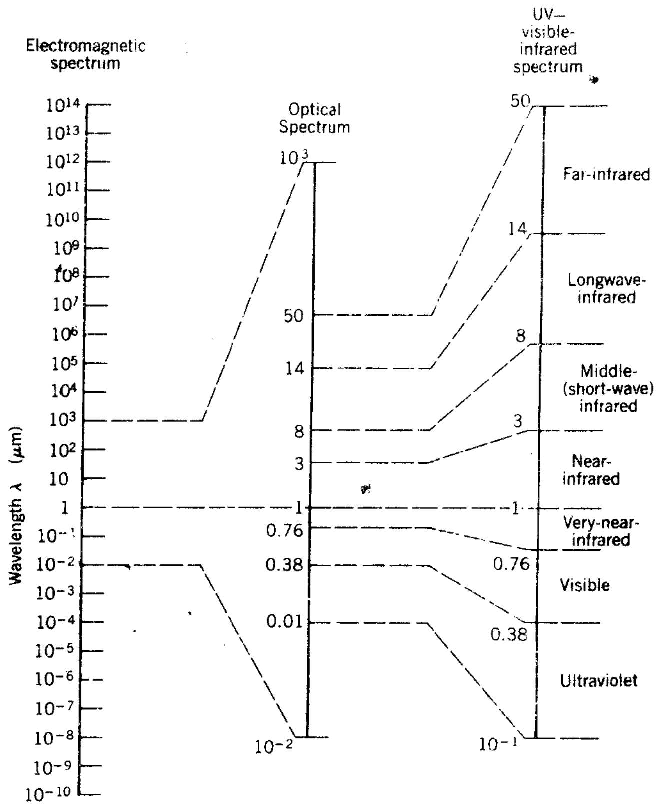

FIGURE 1.1 The optical spectrum.

exceed c in magnitude, the value of the refractive index for any medium is always greater than or equal to unity.

$$n = \frac{c}{v} \tag{1.5}$$

The optical spectrum is defined to be a subset of the electromagnetic spectrum that includes "optical" wavelengths. The range of wavelengths included in the optical spectrum is not universally agreed upon nor are there rules for determining fixed boundaries within the electromagnetic spectrum. Reference 3 defines the optical spectrum as including wavelengths from 10 nm to 1 mm (or 0.01 to 1000 μm). Of this wavelength range the predominant usage in electro-optical systems is in the subrange from about 0.1 to 50 μm.

Figure 1.1 shows specific regions of the electromagnetic spectrum and identifies various subregions of the optical spectrum. The visible portion of the optical spectrum is identified as the range of wavelengths from approximately 0.380 to 0.760 μm. Other labeled subregions in the optical spectrum such as ultraviolet (UV), near-, middle-, and far-infrared have somewhat arbitrary boundaries that have evolved from practical experience and specific applications over a number of years.

1.4 OPTICAL RADIATION SOURCES

Optical radiation coming from an object has two possible origins. One is the internal activity of the atoms that constitute the object. Energies corresponding to wavelengths in the optical spectrum typically involve transitions of electrons within the atom. As the electrons change energy levels they absorb and/or emit quanta of energy (photons) in the form of electromagnetic radiation. The electrons can be stimulated to make transitions by internal energy, chemical reactions, or external sources of energy (e.g., electromagnetic fields). The intensity and wavelengths of the emitted radiation depend on the nature of the stimulation.

A second source of radiation from an object is reflection or transmission of radiant sources in the ambient environment of the object. Reflection can be due to simple scattering or it may involve absorption and reemission of selected wavelengths. A transmitted wavelength is one that passes through the object. Chapter 2 defines radiometric quantities and units useful for describing optical radiation in quantitative terms. Also given in chapter 2 are details of specific sources of optical radiation, including blackbody sources, spectrally selective sources such as LEDs, and coherent sources such as lasers. Ambient sources such as the sun, moon, and earth are also described in chapter 2.

1.5 OPTICAL PATH

Any system that relies on the propagation of optical fields between two points in space must consider the optical properties of the propagation path. The optical path typically is the atmosphere, free space, an optical fiber, the ocean, or some other propagation medium. One parameter of interest for the propagation medium was defined earlier as the refractive index of the medium, which gives information about the speed of propagation. If the refractive index for a particular propagation medium is a function of spatial coordinates (x, y, z) and time, then the effect is not easily described. Typically the propagation path can be described in terms of two properties that affect the optical radiation. These two properties are scattering and absorption. They affect the time dispersion, spatial resolution, contrast, and spatial jitter (fluctuation in the pointing position) of optical radiation propagating through the medium. These parameters affect the performance of many electro-optical systems and can become the limiting factor for performance of the system. A detailed description of all the research methods used in characterizing optical propagation media is beyond the scope of this book. In chapter 10 a development is given that defines fundamental concepts, and a summary is given of pertinent work being done to characterize the optical properties of the atmosphere and of optical fibers.

1.6 DETECTION OF OPTICAL RADIATION

An area of major importance to many electro-optics applications is that of "detecting" optical radiation. Detection consists of converting the optical field into a more readily measurable form. In most detectors, conversion is from optical power (flux) to an electrically measurable parameter such as current, voltage, resistance, or capacitance.

Most electro-optical detectors can be classified as one of two major types: quantum detectors (photodetectors) or thermal detectors. Quantum detectors absorb quanta of optical radiation energy resulting in a change in the energy state of electrons in the detector material. A quantum detector can be photovoltaic, photoconductive, or photoemissive. Because the absorption of quanta is possible for only a finite range of photon energies (dependent upon the available energy states and the energy gap between bound states and the conduction band in the detector material), quantum detectors typically respond to a relatively narrow range of photon energies (and consequently, wavelengths). Thermal detectors, on the other hand, respond to absorbed optical radiation with increased thermal (vibrational) energy within the detector material. This thermal response is relatively independent of the photon energy so that thermal detectors have a wideband response (over many wavelengths).

Although the specific performance of a detector depends on the type of response, physical parameters, and temperature, some general comparisons can be made between quantum and thermal detectors. Their wavelength dependence has already been discussed. Additionally, quantum detectors are generally more sensitive and have faster response times than thermal detectors. However, thermal detectors typically are simpler and less expensive to fabricate. Chapter 5 gives details of the various types of quantum and thermal detectors and gives relative performance parameters for each.

A special area of interest for many current and future electro-optical systems is the development of large-scale two-dimensional arrays of detector elements that are sensitive in different wavelength regions. Chapter 7 gives a description of the various technologies that show promise for accomplishing manufacture and readout of large-scale detector arrays. Performance evaluations are given for state-of-the-art detector arrays. Chapter 7 also describes the operating principles of some commonly used image tubes such as the vidicon, image orthicon, and pyroelectric vidicon. These devices have application in many areas and are an important element of a number of optical detection systems. Hybrid combinations of discrete detector arrays and electron-beam readout are discussed.

1.7 GEOMETRIC OPTICS, PHYSICAL OPTICS, AND ELECTRO-OPTICS

Certain fundamental principles of geometric and physical optics are helpful in understanding the analysis of electro-optical systems. Furthermore, a presentation on electro-optics requires at least an introduction to the concepts of optical path function, the laws of geometric optics, interference, and diffraction.

Chapter 3 covers elementary principles of geometric optics, defines relationships for simple optical instruments, and gives comparisons of selected optical-system types. The optical path function, together with the three laws of geometric optics, form the basis for a rigorous treatment of any optical system. These principles are defined, as are common types of lens defects and aberrations.

Two basic principles of physical optics are interference and diffraction. Interference between two optical wavefronts forms the basis for several electro-optical instruments. Diffraction and diffraction gratings are important in measurements of the optical spectrum and in coherent optical data processing systems.

1.8 ELECTRO-OPTICAL SYSTEMS ANALYSIS

Since electro-optical systems typically interact with propagating optical fields, they exhibit characteristics that are described in terms of two or three spatial dimensions and/or time. Further, many electro-optical systems can be classified as either linear or quasilinear. Thus, the body of knowledge available for describing linear-system performance is applicable to electro-optical systems as well. In particular, system functions such as the impulse response, step response, and transfer function are used to describe electro-optical systems (where these functions are defined to include the appropriate combination of temporal and spatial dependence). Electro-optical system performance is typically characterized in terms of two fundamental quality measures: noise performance and signal-to-noise ratio, and spatial and temporal performance (resolution, coherence, contrast). A number of related performance parameters and functions are defined throughout the book. Chapter 6 in particular attempts to formalize the analysis methods and define specific system functions useful for characterizing most electro-optical systems. Specifically, the optical transfer function (OTF), modulation transfer function (MTF), and point spread function (PSF) are spatial analogs of the more familiar transfer function, amplitude frequency response, and impulse response function used to describe linear time-invariant systems.

The signal-to-noise ratio is very important for describing the performance of electro-optical sensors and other systems where the optical radiation is attenuated significantly by the propagation medium. Noise equivalent power (NEP), noise equivalent flux density (NEFD), and detectivity are noise-related performance parameters that are used in addition to signal-to-noise ratio to define system performance.

1.9 ELECTRO-OPTICAL APPLICATIONS

This section contains brief descriptions of the operating principles of a number of selected electro-optical systems. It is intended to give the reader a better feeling for the kinds of systems that can be called electro-optical. An overall systems point of view is presented. More detailed descriptions and analysis methods are given in later chapters for some of the systems.

1.9.1 Electro-Optical Sensors

An electro-optical sensor may be imaging or nonimaging, depending upon the particular purpose of the system. In either case the total system consists of a number of interrelated elements such as optics, detector, electronics, signal processing and control. All these elements must be considered in the detailed design of an electro-optical sensor. The analysis, design, and characterization of electro-optical sensors is an area of electro-optics that has been very important in the past and will become even more important in the future as detector arrays containing millions of detectors become available. Imaging sensors will find increasing application in intelligent robotics systems for military, industrial, and even entertainment systems.

An imaging sensor must either have an array of detectors to provide coverage of a specified field of view or it must scan optically (or mechanically) a small number of detectors over the total field of view. If a sensor is nonimaging, then its only purpose is the detection of radiant energy within specified wavelength bands. Simple relationships among detector size, optics size, and range to an object from the sensor are developed in chapter 8 to illustrate further the practical constraints on imaging versus nonimaging applications.

Sensor performance is described primarily in terms of output-signal-to-noise ratio and spatial resolution. These performance measures typically have a complicated dependence on numerous other parameters so that a detailed analysis can proceed only so far without specifying some of the parameter values. Chapters 6 and 8 attempt to bring together all the diverse analysis methods that have been applied to different electro-optical sensor systems and show where the analyses give similar expressions for the same quantities. The approach is fundamental and provides a sound background in the methods for analyzing any electro-optical sensor system.

1.9.2 Optical Signal Processing

An important application of electro-optics is the processing of signals, or data, optically. The data may be one-dimensional time signals or two-dimensional spatial signals. Optical signal processing may be defined as the implementation of signal-processing algorithms using optical methods. Thus, the computation of Fourier transforms and correlation functions and the implementation of filters are examples of optical signal processing.

Coherent optical signal processing requires a coherent optical source such as that provided by a laser. Additionally, many optical processing methods require high-quality optical components and precision alignment methods. The major advantage of an optical processor is its speed. The processing takes place in real time, whereas similar processing done on a digital computer can take much longer to accomplish. Much of this speed advantage of the optical processor is lost, however, because of the cumbersome ways in which data are input and readout of the optical system. For example, one method of inputting and outputting data requires exposure and processing of photographic film. Near-real-time input-out-