INDUSTRIAL

LASERS

AND THEIR APPLICATIONS

SECOND
EDITION

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To Our Wives,
Sally and Nancy

Preface to Second Edition

The purpose of this book, as described in the Preface to the first edition, has not changed. In the second edition we have tried to clarify some areas, simplify where necessary, add appropriate material, delete inappropriate or irrelevant material, and update to the extent that it is practical in the rapidly developing field of industrial laser applications. There has been no attempt to make this book an exhaustive encyclopedia of lasers and laser applications. For example, microelectronics applications are not covered; that would require a large book in its own right. What we have done is try to produce an introduction to lasers and industrial applications that provides the fundamentals in a readable fashion and enough information for a student, scientist, or engineer to intelligently and appropriately apply lasers in industrial situations.

Chapter 1, Principles of Optics, has been expanded to include sections on enhanced and antireflection coatings, electro-optical modulators, and optical materials. The section on optical resonators has been moved from Chapter 6, Laser Theory, to Chapter 7, Laser Beam Properties, to provide better continuity in the area of laser optical properties. The notation in Chapter 7 has been significantly simplified, as has the entire discussion of beam propagation and focusing, without sacrificing content or the usefulness of the

material. A section on excimer lasers has been added to Chapter 8, Types of Lasers.

Chapters 9 and 10, which deal with low-power applications of lasers, have been expanded to three chapters and a substantial amount of new material has been added. Chapter 9, Using Low-Power Lasers for Alignment, Gaging, and Inspection, deals with devices and techniques used in industry that require structured laser light, but not the accuracy that can be obtained by using interferometry. Similar applications have been grouped and preceded by a discussion of relevant optical design concepts. This is followed by a rather complete discussion of interferometric applications in Chapters 10 and 11. Chapter 10, Introduction to Interferometry, is designed to review fundamentals used in both chapters and discuss industrial applications of traditional interferometric techniques that have benefited by the advent of the laser. Chapter 11, Holographic and Speckle Interferometry, has been expanded and includes new material on thermoplastic holographic plates, carrier fringe techniques, and speckle interferometry.

Chapter 11, Interaction of High-Power Laser Beams with Materials, is Chapter 12 in the new edition. Material that was found to be extraneous or irrelevant has been removed from this chapter, making it much more readable. A new section on material removal has been added, and the section on welding has been expanded. Chapter 12, High-Power Laser Applications, is Chapter 13, High-Power Systems and Applications, in the new edition. A section on beam delivery for high-power systems and a subsection on polarization effects have been added to this chapter.

Many other changes have been made that we believe will increase the value and usefulness of this book. These include corrections, new photographs, and additional problems in many chapters.

James T. Luxon
David E. Parker

Preface to First Edition

The purpose of this book is to provide the reader with an introduction to lasers and their industrial applications. To facilitate this objective, such devices as photodetectors and modulators, which are frequently found in laser applications, are also covered. And to make the book as self-contained as possible, the concepts of basic optics that are pertinent to lasers and their applications are presented. Many engineering students do not cover this material formally in their course work; moreover, many working engineers and scientists either have not had training in optics or have been away from it for a long time and may need a refresher. Some laser theory is presented to provide a working understanding of the laser and to clear away the mysticism surrounding the device. When tools are understood, they are used more frequently and used properly.

The topic of laser beam optics, including propagation, focusing, and depth of focus, is covered in some detail for both Gaussian and higher-order mode beams because such information is of practical value to industrial applications of lasers.

A chapter on optical detectors, including detector arrays, is preceded by a short chapter on semiconductors, to enhance the understanding of solid-state optical devices, and by a chapter in which radiometry, photometry, and optical device parameters are discussed.

It would be impossible to present an exhaustive treatment of the interaction of high-power laser beams and matter, but some of the most pertinent cases are presented in a chapter on laser beam materials interaction. Separate chapters are devoted to industrial applications of low- and high-power lasers. Specific types of applications are presented, along with additional theoretical or conceptual material where required.

This is not a book on lasers but rather a book that is intended to help prepare engineering students or practicing engineers and scientists for the practical application of lasers in an industrial manufacturing setting. Thus the book may be used for a one-semester, junior-senior level course on lasers and laser applications or by practicing engineers and scientists who need to learn quickly the essentials of lasers and their applications. Greater depth in the topics on lasers or materials interactions, for example, can then be obtained from many more advanced books.

This book can be used in several different ways. The first chapter on basic optics can be omitted if the reader has a background in optics. The chapters on semiconductors, parameters, radiometry, and devices can be omitted if the reader's interests do not lie in these areas; these topics are not essential to the remainder of the book.

Readers who have some familiarity with lasers and their properties can omit the overview chapter on lasers. Any chapters on low- or high-power applications may be omitted without loss of continuity.

The authors are greatly indebted to a number of people. We want to express our appreciation to our families for their patience and encouragement. We would like to thank many of our students who gave us constructive criticism and other assistance. We would particularly like to thank Mark Sparschu and Jim McKinley for reading Chapters 9 and 10 and working the problems. We also want to thank Ms. Barbara Parker for her skillful proofreading and Ms. Judy Wing for her patience, skill, and good humor in typing much of the manuscript.

James T. Luxon
David E. Parker

Contents

Chapter 1

Principles of Optics

This chapter is intended to provide the reader with a basic working knowledge of the principles of optics, including a description of the nature of electromagnetic radiation, as well as geometrical and physical optics. This chapter also provides a basis for much of what follows in subsequent chapters.

1-1 NATURE OF ELECTROMAGNETIC RADIATION

Electromagnetic radiation exhibits both wavelike and particlelike characteristics, as does matter when it comes in small enough packages, like electrons. Both aspects of electromagnetic radiation are discussed and both are relevant to understanding lasers. From the point of view of its wavelike characteristics, electromagnetic radiation is known to exhibit wavelengths from less than 10^{-13} m to over 10^{15} m. Included in this range, in order of increasing wavelength, are gamma rays, x rays, ultraviolet waves (uv), visible light, infrared (ir) light, microwaves, radio waves, and power transmission waves. Figure 1-1 illustrates the various parts of the range of electromagnetic waves as a function of wavelength.

The sources of gamma rays (γ rays) are nuclear transitions involving
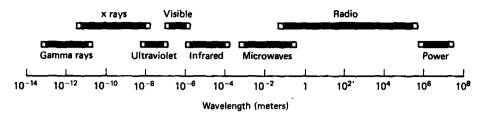
Figure 1-1   Electromagnetic radiation as a function of wavelength.

radioactive decay. X rays are produced through electronic transitions deep in the electronic structure of the atom. Ultraviolet waves result from electronic transitions involving fairly high energy and overlap the x-ray region somewhat. Visible radiation extends from about 0.35 to 0.75 μm and is due to electronic transitions, primarily of valence electrons. Infrared radiation results from electronic transitions at the near visible end and molecular vibrations toward the long-wavelength end. Microwaves and radio waves are produced by various types of electronic oscillators and antennas, respectively.

The term *light* is used loosely to refer to radiation from uv through ir.

The wavelike properties of electromagnetic radiation can be deduced from the wave equation presented here in one-dimensional form:

$$\frac{\partial^2 E}{\partial z^2} = \frac{1}{c^2}\frac{\partial^2 E}{\partial t^2} \tag{1-1}$$

where c is the velocity of light and E is the electric field intensity. The wave equation can be derived from Maxwell's equations, the foundation of all classical electromagnetic theory. The symbol E in Eq. (1-1) may represent any one of the various electromagnetic field quantities, but for our purposes the electric field intensity is of greatest interest.

Another relationship that can be deduced from Maxwell's equations that is of use to us is Poynting's theorem:

$$\mathbf{S} = \mathbf{E} \times \mathbf{H} \tag{1-2}$$

where $\mathbf{S}$ is power flow per unit area, $\mathbf{E}$ is electric field intensity, and $\mathbf{H}$ is magnetic field intensity. For a freely propagating electromagnetic wave, it reduces to

$$S_{ave} = \tfrac{1}{2}EH \tag{1-3}$$

where S_{ave} is the average power flow per unit area and E and H are amplitudes.

Light may be thought of as being composed of sinusoidal components of electric and magnetic fields from the point of view that electromagnetic radiation is a wave. For a simple electromagnetic wave propagating in an

unbounded medium (the electric field varying parallel to a single direction, referred to as *linear polarization*), the wave may be schematically represented as in Fig. 1-2.

The electric and magnetic fields are oriented at right angles to each other and to the direction of propagation z. **E**, **H**, and z form a right-hand triad; that is, **E** × **H** gives the direction of propagation. Ordinary (unpolarized) light contains a mixture of polarizations in all directions perpendicular to the direction of propagation. Because of the vector nature of the electric field, unpolarized light can be thought of as an equal mix of electric field strength in orthogonal directions, say x and y, with random phase relations between the various contributions to the electric field. The significance of this statement will become apparent later on.

The speed of propagation in free space (vacuum) is approximately 3×10^8 m/s and is equal to $1/\sqrt{\mu_0 \epsilon_0}$ according to classical electromagnetic wave theory. For an electromagnetic wave propagating in a dielectric medium, the speed is

$$\frac{1}{\sqrt{\mu \epsilon}} = \frac{1}{\sqrt{\mu_r \mu_0 \epsilon_r \epsilon_0}} = \frac{c}{\sqrt{\mu_r \epsilon_r}}$$

where c is the speed of light in free space and μ_r and ϵ_r are the relative permeability and permittivity of the medium, respectively. In nonmagnetic materials $v = c/\sqrt{\epsilon_r}$. The refractive index of a dielectric medium is defined by

$$n = \frac{c}{v} \qquad (1\text{-}4)$$

and so it is seen that $n = \sqrt{\epsilon_r}$ for most dielectrics.

It is possible to show that $E = ZH$, where Z is called the intrinsic impedance of the medium. This fact can be used to put Eq. 1-3 in the form

$$I = \frac{1}{2} \frac{E^2}{Z} \qquad (1\text{-}5)$$

where I is the irradiance (power per unit area). You may recognize the similarity between Eq. (1-5) and the equation for Joule heating in a resistor,
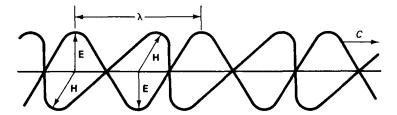

Figure 1-2 Propagation of a linearly-polarized electromagnetic wave.

which is $P = V^2/R$, where P is power, V is voltage, and R is resistance. The one-half does not appear in the Joule's law heating equation because V is a root mean square rather than an amplitude.

The intrinsic impedance of an unbounded dielectric is $Z = \sqrt{\mu/\epsilon}$, where $\sqrt{\mu_0/\epsilon_0}$, the intrinsic impedance of free space, is 377 Ω. Then

$$Z = \frac{377 \; \Omega}{\sqrt{\epsilon_r}} = \frac{377 \; \Omega}{n} \tag{1-6}$$

for nonmagnetic dielectrics. Equation (1-5) can therefore be written

$$I = \frac{1}{2} \frac{E^2 n}{377 \; \Omega} \tag{1-7}$$

The subject of electromagnetic wave propagation in conductors is beyond the scope of this book, but a few pertinent facts can be pointed out. The impedance of a good conductor is given by

$$Z = \sqrt{\frac{\mu\omega}{\sigma}} \; e^{-j(\pi/4)} \tag{1-8}$$

where ω is the radian frequency of the light and σ is the conductivity of the conductor. As can be seen from Eq. (1-8), Z is a complex impedance. E is very small in a conductor; H is large. When an electromagnetic wave strikes a conductor, E will go nearly to zero and H becomes large due to large induced surface currents. The results are considerable reflectance of the incident wave and rapid attenuation of the transmitted wave. The skin depth, which is a measure of how far the wave penetrates, is given by

$$\delta = \frac{1}{\sqrt{\pi\mu\sigma f}} \tag{1-9}$$

For frequencies of interest in this book, chiefly visible and ir to 10.6 μm, δ is extremely small and absorption can be assumed to take place at the surface for all practical purposes.

Based on the Drude free electron theory of metals, it can be shown that the fraction of the incident power absorbed by a metal is given approximately by

$$A = 4\sqrt{\frac{\pi c \epsilon_0}{\lambda \sigma}} \tag{1-10}$$

The reflectance is $R = 1 - A$, which, for copper with $\sigma = 5.8 \times 10^7$ (Ω-m)$^{-1}$ at $\lambda = 10.6$ μm, leads to $R = 0.985$. Actual reflectances may exceed this value for very pure copper. For highly polished or diamond-turned copper mirrors, the reflectance exceeds 0.99.

The particlelike behavior of electromagnetic radiation is exhibited in