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INDUSTRIAL LASERS AND THEIR APPLICATIONS

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Preface

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-power 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-power 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.

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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 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 μm 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

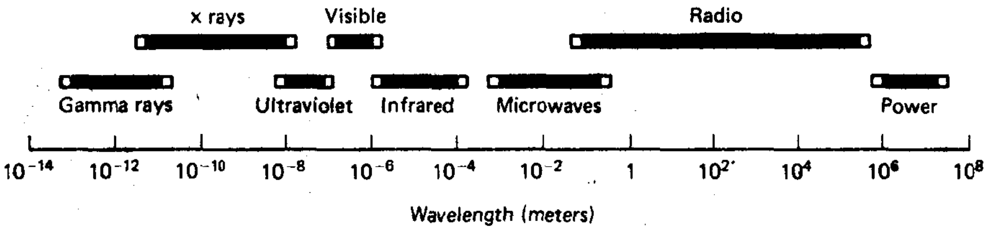

Figure 1–1 Electromagnetic radiation as a function of wavelength.

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 **S** is power flow per unit area, **E** is electric field intensity, and **H** is magnetic field intensity. For a freely propagating electromagnetic wave, it reduces to

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

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 as an equal mix of electric field strength in orthogonal

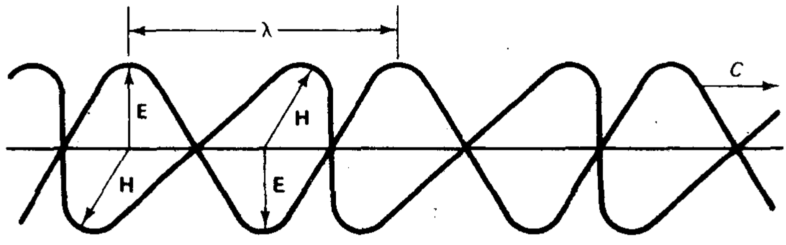

Figure 1–2 Propagation of a plane-polarized electromagnetic wave.

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, 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 377Ω. Then

$$Z = \frac{377\Omega}{\sqrt{\epsilon_r}} = \frac{377\Omega}{n} \qquad (1\text{–}6)$$

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

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

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 $\sigma = 5.8 \times 10^7 (\Omega - \text{m})^{-1}$ at $\lambda = 10.6\ \mu$m, 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 many experiments, such as the photoelectric effect and Compton scattering. It was in an explanation of the photoelectric effect in 1905 that Einstein proposed that electromagnetic radiation (light for short) is composed of bundles of energy, quanta, which are referred to as *photons.* The energy of each of these photons, he argued, is hf, where h is Planck's constant ($h = 6.6 \times 10^{-34}$ J · s). Planck had determined this constant previously in explaining the dependence of blackbody radiation on frequency.

In 1924 DeBroglie proposed a mathematical model for the photon. This model consists of an infinite sum of waves of different frequencies within a finite frequency range with an appropriate amplitude function. It was really nothing more than a Fourier integral representation of a finite pulse, with the amplitude function chosen to produce a wave packet with minimum uncertainty products. A schematic representation of such a pulse is given in Fig. 1–3. The outer solid lines form an envelope of the amplitude of the actual wave. The uncertainties referred to concern the length of the packet L, its relation to the uncertainty in its momentum Δp, and the relation between frequency bandwidth and the time it takes the photon to pass a given point. These relations are

$$\Delta pL \leq \frac{h}{2\pi} \tag{1–11}$$

$$\Delta f\, \Delta t \leq \frac{1}{2\pi}$$

These relations will be useful later on in discussing coherence of light sources.

DeBroglie proposed a duality of both light and matter; that is, he suggested that matter should exhibit both wave and particle characteristics. It was later shown that electrons can be diffracted by crystals and the observed wavelength agreed with that predicted by DeBroglie. The DeBroglie wavelength can be deduced by setting Einstein's famous mass energy relationship $E = mc^2$ equal to the energy of a photon hf. Thus

$$E = mc^2 = hf$$

and $mc = hf/c$ is the momentum of a photon, and therefore momentum and wavelength are related by

$$p = mc = \frac{h}{\lambda} \tag{1–12}$$

This relation holds for both light and matter waves. These results can be used to show (left as an exercise for the student) that $dp/dt = P/c$ for a total absorption at a surface, where P is total power in the beam and c is the speed of light. The radiation pressure is dp/dt divided by the area of incidence. In general, this pressure can be written

$$\frac{F}{A} = \frac{(1 + R)P}{cA} \tag{1–13}$$

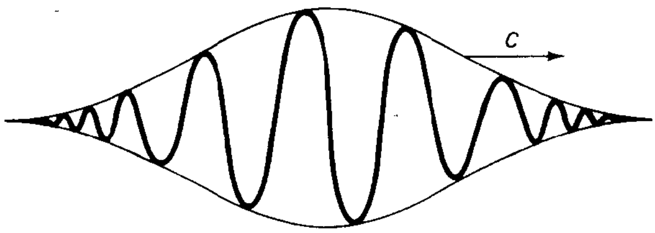

Figure 1–3 Schematic representation of mathematical model of a photon.

where R is the fraction of the incident power reflected and A is the area of incidence. This pressure can be substantial for a focused laser beam.

1-2 REFLECTION AND REFRACTION

The *law of reflection* states that, for specular reflection of light, the angle of incidence equals the angle of reflection. This situation is illustrated in Fig. 1–4. The reflected ray lies in the same plane as the incident ray and the normal to the surface. This plane is referred to as the *plane of incidence.* A specular surface is one with a surface finish characterized by rms variations in height and separation of peaks and valleys (surface roughness) much less than the wavelength of the light. In other words, a surface that is not a good specular surface in the visible could be quite specular at longer wavelengths. This is an important point to remember when working around high power—long wavelength lasers.

Most surfaces cause reflected light to contain a portion of specular and diffusely reflected (scattered) light. The diffuse reflection is the result of random reflections in all directions due to roughness of surface finish. An ideal diffuser scatters equal amounts of power per unit area per unit solid angle in all directions. Hence a perfect diffusing surface is equally bright from all viewing angles. Few surfaces approach the ideal case.

The law of refraction, or *Snell's law* as it is commonly called, is given by Eq. (1–14) and the angles are defined in Fig. 1–5.

$$n_1 \sin \theta_1 = n_2 \sin \theta_2 \tag{1-14}$$

The law of reflection applies equally to all materials whereas Snell's law, in the form given in Eq. (1–14), is valid only for an interface between two dielectrics.

Two phenomena of importance relate simply to Snell's law. The first, total internal reflection (TIR), occurs when light travels from a medium of higher refractive index into one of the lower refractive indices. Because $n_2 < n_1$, Snell's law requires that $\theta_2 > \theta_1$. At an angle of incidence called the critical angle θ_2 becomes 90°. At this angle of incidence θ_c, and for all $\theta_1 > \theta_c$, all

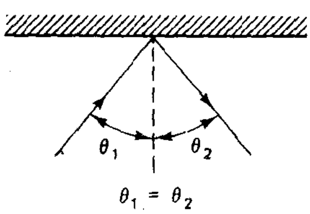

Figure 1–4 Law of reflection.

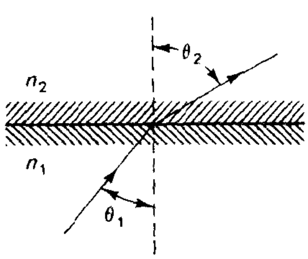

Figure 1–5 Refraction at a dielectric interface.

incident power is reflected. The critical angle is deduced from Snell's law to be

$$\theta_c = \sin^{-1}\frac{n_2}{n_1} \tag{1-15}$$

The second phenomenon is Brewster's law, which has significance in many laser designs as well as other areas. Brewster's law states that when the reflected and refracted rays are at right angles to each other, the reflected light is linearly polarized perpendicular to the plane of incidence. The angle of incidence at which this occurs is called the Brewster angle θ_B. Figure 1–6 illustrates this phenomenon. Because θ_2 is the complement of θ_B, Snell's law gives

$$n_1 \sin\theta_B = n_2 \cos\theta_B \tag{1-16}$$

or

$$\theta_B = \tan^{-1}\left(\frac{n_2}{n_1}\right)$$

This is a reversible phenomenon, unlike TIR, and the Brewster angle from side 2 to 1 is $90° - \theta_B$ or $\tan^{-1}(n_1/n_2)$.

When light is incident on a surface, a certain fraction of the light is absorbed or transmitted and the remainder is reflected. The fraction of power reflected, called the reflectance R, for light normally incident on an interface between two dielectrics is given by

$$R = \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2 \tag{1-17}$$

If light is incident from side 1, there will be a 180° phase shift in the reflected wave for $n_2 > n_1$ but no phase shift if $n_2 < n_1$. This factor is important for antireflection and enhanced reflection coatings on optical components.

For nonnormal angles of incidence, the Fresnel formulas provide the reflectances for parallel and perpendicular polarizations.

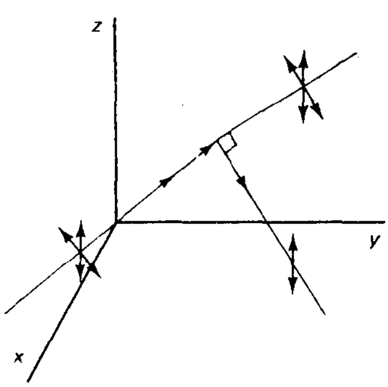

Figure 1–6 Illustration of Brewster's law. Interface is the yz plane and rays are parallel to the xy plane.

$$R_{\parallel} = \left[\frac{\tan(\theta_1 - \theta_2)}{\tan(\theta_2 + \theta_1)}\right]^2$$
$$R_{\perp} = \left[\frac{\sin(\theta_2 - \theta_1)}{\sin(\theta_1 + \theta_2)}\right]^2 \quad (1\text{–}18)$$

Note that $R_{\parallel}$ goes to zero for $\theta_2 + \theta_1 = 90°$, the Brewster angle condition.

1-3 MIRRORS AND LENSES

In this section the results derive from the application of the law of reflection to mirrors and Snell's law to thin and thick lenses. Pertinent information concerning spherical aberration is also presented.

The sign convention used here, with regard to lenses and mirrors, follows that of Jenkins and White, 1976. In this convention, light is always assumed to be traveling left to right. All object or image distances measured to the left of a reflecting surface are positive; otherwise they are negative. Object distances to the left and image distances to the right are positive for refracting surfaces; otherwise they are negative. Radii of curvature are positive if measured in the direction of the reflected or refracted light; otherwise they are negative. Lenses or mirrors that converge parallel rays have positive focal lengths and negative focal lengths if they diverge parallel rays. An object height measured above the axis is positive; below the axis it is negative.

Figure 1–7 illustrates the effect of concave (positive) and convex (negative) spherical mirrors on parallel rays.

Parallel rays are reflected through a point called the focal point F for the concave mirror. Point C locates the center of curvature and F lies midway between C and the vertex of the mirror. Hence f, the focal length or distance from F to the vertex, equals $r/2$, where r is the radius of curvature of the mirror. For the convex mirror, rays parallel to the axis are reflected such that they appear to be coming from the focal point F. For the concave mirror, rays parallel to the axis are reflected through the focal point. In both cases,

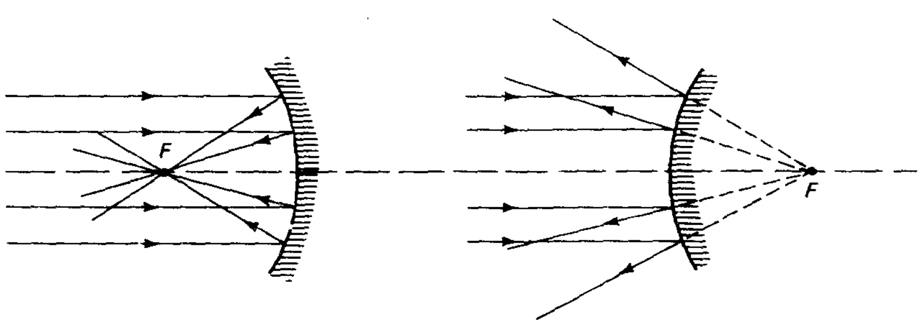

Figure 1–7 The effect of concave and convex mirrors on rays parallel to the axis.