OPTICAL PHYSICS

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PREFACE

Recent years have seen the ascendency of a field which can be described as the interactions of radiation and matter in the optical spectrum, here quite generally defined as the region bounded by microwaves and x-rays, containing the infrared, visible, and ultraviolet wavelengths. To a major extent, the growth in importance of this field is due to the maturity which certain of its experimental techniques have reached, especially those of generating and detecting monochromatic or continuum radiation over this entire range of frequencies. These practical advances in turn have had two major consequences. First, they stimulated —and made possible—more basic inquiries into such diverse topics as higher order coherence, the generation of stimulated emission from inverted populations, solid state spectra, and phenomena of photoconductivity. Second, there has emerged a wealth of applications, from detectors of far infrared radiation to sources of ultraviolet laser beams. The purpose of this book is to describe by means of a unified treatment the various interaction phenomena, their experimental and theoretical exploration, and their applications.

The title "Optical Physics" is chosen so as to convey concisely the two symmetric aspects of the field: The study of dynamic interactions between light and matter and the conclusions on structure and state that can be derived from optical phenomena. Of course, the name "Optical Physics" has been used for more limited and quite diverse subjects, such as the radiative phenomena of gases, the optical properties of solids, or the statistical behavior of light beams. However, these various fields are embraced under the definition adopted here, so that the area to be treated in this book is extensive and diverse. Furthermore, the intent is to present aspects of theory, phenomenological description, and application in about equal measure.

The text material is divided into three major parts, the processes of emission and absorption, the phenomena of propagation, and finally the secondary effects caused by radiation. The first chapter introduces concepts fundamental to the rest of the book, particularly the relationship between structure and radiation. The next three chapters deal with emission and absorption following a sequence of increasingly detailed models: Thermal radiation continua from solids and plasmas, first from the viewpoint of thermodynamics, then of quantum statistics; monochromatic radiation, first from the classical, then from the quantized oscillator; the line shapes for various conditions and degrees of resonance broadening; the spectra from structures in which the complexity is increased stepwise, viz., atoms with single and multiple valence electrons, spins, multipoles, molecules, and finally solids. The next two chapters are concerned with propagation. Chapter 5 treats propagation phenomena in general with regard to the optics of various materials. In Chapter 6 aspects of propagation which are characteristic of coherent light are discussed. This includes criteria and measurement of coherence with such practical applications as intensity interferometry, the theory and practice of optical masers, and nonlinear optics. The last chapter deals with various photoeffects, their applications in detectors, and the theory of fluctuations as the ultimate limit to detection. As this last chapter was being written, it was possible to report on the solution of a problem which had been under attack for many decades: The opening of the entire optical spectrum to photon detectors.

This work is intended as a textbook, even though many of its subjects are still in the forefront of evolving research. For this reason, certain basic theories are briefly stated, their availability in diverse texts notwithstanding. This is particularly true of such subjects as quantum statistics, atomic spectra, and the electromagnetic theory of light. If in such discussions I have followed rather closely the classic treatments—for example, Born's "Atomic Physics," Heitler's "Quantum Theory of Radiation," and Becker-Sauter's "Theorie der Elektrizität," this was done because I could not improve on perfection; in these cases I have cited the source. In all other instances, whenever possible, I have relied on the original research paper, as quoted at the end of each chapter. Nevertheless, the bibliography is in no way complete. It represents only a portion of the available literature; but it is that portion which I have used, or at least read, for this book. Finally, certain ideas and experiments which had been carried out in my Optical Physics Section at the Westinghouse Research Laboratories have been mentioned in this text, although they have been briefly published elsewhere. One area of special interest, the theory and applications of infrared radiation, was initially intended to form a somewhat larger portion of the book. However, the appearance of several good texts on this subject, such as the "Elements of Infrared Technology" by Kruse, McGlauchlin, and McQuistan, made a more extensive discussion of this field unnecessary.

I wish to acknowledge my indebtedness, first of all, to the Westinghouse Research Laboratories for encouragement and cooperation extended to

me in writing this book. Several of my colleagues have assisted in the arduous task of proofreading and with helpful comments, especially Dr. M. Gottlieb and T. P. Vogl, who read this entire manuscript, and Dr. R. D. Haun, Dr. H. F. Ivey, A. H. Boerio, and Mrs. S. Banigan. The treatment of fluctuations and noise in the seventh chapter has been strongly influenced by suggestions from Dr. J. W. Coltman. I have had the benefit of illuminating discussions with Prof. E. Wolf regarding the chapter on coherence phenomena. A number of authors deserve acknowledgment who sent me communications on their work, photographs of spectra, and other material which would be difficult to obtain otherwise, notably Prof. A. Hadni, Dr. R. Tousey, Prof. G. H. Dieke, and Dr. T. P. Hughes. Last but not least, thanks are due to my wife for helping with corrections and for charitably forgoing many a long weekend on behalf of this book.

MAX GARBUNY

Pittsburgh, Pennsylvania
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FUNDAMENTALS OF RADIATION AND ITS INTERACTION WITH MATTER

1.1 Introduction and Orientation

1.1.1 Classical Optics

It is possible to divide the study of optical radiation, historically as well as didactically, into two different parts which may be referred to as classical and modern optics. The first of these consists of optics in its original and more restricted sense, namely, insofar as it is concerned with the understanding of the nature and propagation properties of visible light. This discipline—as old as scientific thought itself—represents one of the original divisions of physics according to the human senses, viz., that dealing with the perceptions of vision. Characteristically, throughout most of its history, it remained a science isolated by itself, having little interaction with the other fields of physics. Here belong such major subdivisions as geometric optics, which had its beginnings among the treatments of early Greek mathematicians and reached its highest sophistication with the mathematical theorems of Fermat (1601–1665) and Malus (1755–1812); and the various manifestations of physical optics, such as interference, first observed by Boyle (1626–1691) and Hooke (1635–1703), diffraction (Grimaldi, 16th century; Fresnel, 1816), and polarization.* All these phenomena, including those connected with the velocity of light in vacuo and other media, could be explained by a system of differential equations, stated by Maxwell (1873) in terms of interrelated and time-variant electric and magnetic fields.

1.1.2 Electromagnetic Spectrum

Now this electromagnetic theory of light marks not only the culmination, but, in a sense, also the conclusion of the "pure" or classical optics which it is able to explain. Thus began the age of modern optics where

* See also historical introduction and beginning of Chapter 8 in Born and Wolf.[1]

the emphasis is placed on the interaction between radiation and matter, particularly in atomic processes. The reason for this lies in the consequences of Maxwell's equations themselves. These emphatically state that the nature and propagation properties of light are explainable in terms of another discipline of physics, viz., that of electromagnetism. Therefore, the interaction between light and matter, especially the processes governing the emission and absorption of radiation, cannot be understood unless the structure of matter is known to the extent to which it determines the electromagnetic behavior. This, it will be seen, involves an entirely new area of study, concerned with electrons, ions, atoms and their structural bonding. Again, the electromagnetic theory of radiation introduces the fact that light, to the extent to which it is perceptible by the human eye, is merely part of an infinite continuum the electromagnetic spectrum.

These disclosures of the theory did not find the scientific world altogether unprepared. Already in 1800, W. Herschel, endeavoring to measure the caloric content of the solar spectrum, had found that heat radiation was received in the invisible portion beyond the red. This *infrared* emission was found in succeeding experiments to exhibit the salient properties of wave propagation and other characteristics of visible light, although both generation and detection were accomplished at that time exclusively by thermal processes. The existence of a spectrum beyond the visible violet was discovered almost simultaneously with infrared. In 1801 J. W. Ritter found that radiant energy in that region produced blackening in silver chloride, and subsequent interference experiments by Young (1804) allowed the conjecture that this *ultraviolet* radiation was of the same nature as visible light.

Altogether, it is now known that the electromagnetic spectrum (see Fig. 1.1) encompasses radio- and microwaves, infrared, visible, and ultraviolet light, x (or Roentgen-) rays, gamma, and cosmic radiation. All of these have in common that they propagate through space as transverse electromagnetic waves; and that in vacuo their speed of propagation which is the product of their frequency and their wavelength, is the same for all, the speed of light. We write

$$\lambda\nu = c \tag{1.1}$$

where λ is the wavelength, ν the frequency, and c the propagation velocity of light in vacuo which is almost exactly 3×10^{10} cm/sec. The various parts of the electromagnetic spectrum differ in wavelength and frequency, and this, in turn, leads to profound differences in their generation and their interaction with matter. Thus, the spectral regions are distinguished

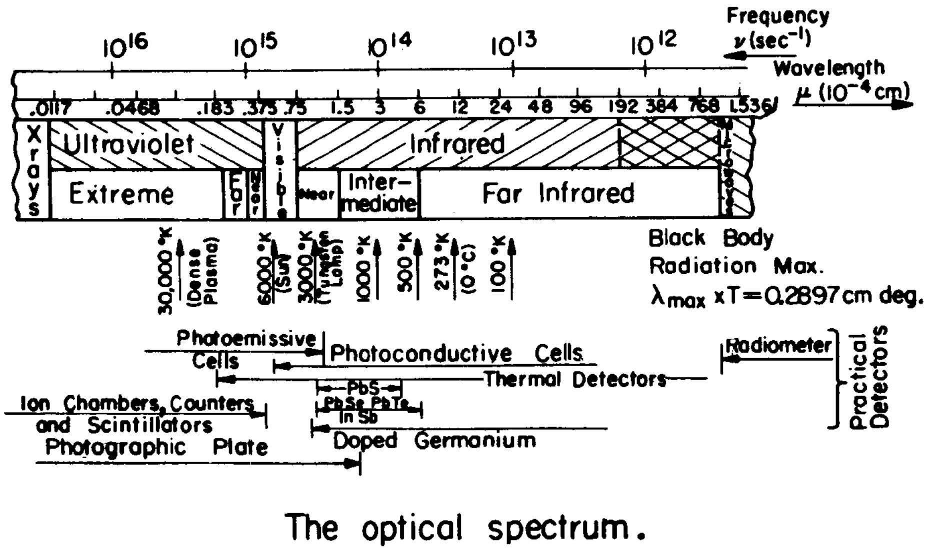

FIG. 1.1. The electromagnetic spectrum at and around the optical region. Position of black body radiation maxima is indicated on wavelength scale for various absolute temperatures. Spectral range of operation is indicated for various practical detectors.

by the methods of generating or observing their wavelengths, and their limits are fixed by convention rather than by sharp discontinuities of the pertinent physical phenomena. Radiation at lowest frequency is produced and received by electron beam tubes in combination with extended resonant structures of capacitors and inductances between which the energy oscillates (see Fig. 1.2). In the microwave region, at successively higher frequencies, the structures shrink, and the interplay between electric and magnetic fields is supported by single components, viz., cavities and waveguides. At yet shorter wavelengths, we have to turn to the oscillators provided by nature: molecules, rotating and vibrating in the infrared; electrons performing transitions across atomic fields in the visible and ultraviolet regions. The mechanism by which radio frequency oscillations are produced is still recognizable, at least in principle, on the molecular scale; but the radiation is now generated, not in a single oscillator, but typically by an enormous number of individual vibrators, and this engenders totally different phenomena and techniques of experimentation. Finally, at still higher frequencies, radiation is encountered which is produced either by charged particle bombardment, as in the case of *x* rays and certain cosmic rays, or by nuclear transitions, as in the case of gamma radiation and certain other cosmic rays. Taken as a group, these radiations are characterized by the high energy involved in their generation and by the fact, to be described later, that they behave like corpuscles rather than waves in their interaction with matter.

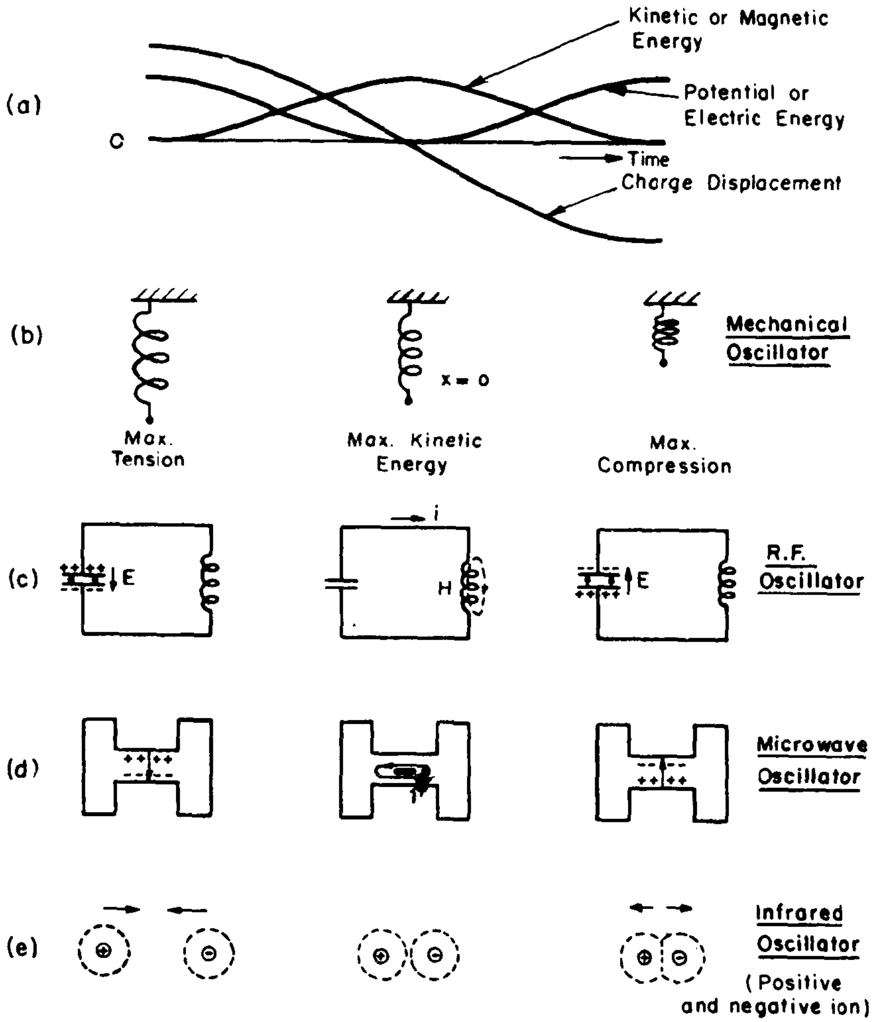

FIG. 1.2. The oscillator as periodic converter of energy from one form to another. Mechanical oscillators (b) change from potential to kinetic energy and back. Their electric analogues shown for various wavelength regions (*c–e*) oscillate between electrostatic and magnetic field energy. Phase relationship of the various parameters is shown in (a).

1.1.3 The Optical Spectrum

It has become apparent in the preceding paragraph that the electromagnetic spectrum consists of three major portions: (1) the very energetic (corpuscular type) emission from nuclear and bombardment processes at the high-frequency end; (2) the radio and radar waves generated in extended circuit structures at the long wavelength end; and (3) in the intermediate region, the radiations of light which exhibit, as will as be seen, both wave and particle character, and which have their origin in atoms and molecules. This third group, which includes (see Fig. 1.1) the infrared, visible, and ultraviolet wavelength regions, constitutes the optical spectrum in the wider sense. The justification for this collective name is based, not merely on the close relationship of the emission processes, but on common experimental techniques, such as the use of lenses and mirrors for focusing purposes and of prisms and gratings for spectroscopy, although the various spectral regions within this group must be accommodated by proper choice of materials and design of components.

TABLE 1.1

Conversion Factors and Units

Lengths

1 micron (μ)	$= 10^{-3}$ mm $= 10^{-4}$ cm
1 angstrom (Å)	$= 10^{-8}$ cm $= 10^{-4}\ \mu$
1 millimicron (mμ)	$= 10^{-7}$ cm $= 10$ Å
1 centimeter (cm)	$= 0.3937$ in. $= 1 \times 10^{4}\ \mu = 0.010936$ yard
1 mile (mi) U.S. Statute	$= 1.609$ km $= 1.609 \times 10^{5}$ cm
	$= 1.69 \times 10^{-13}$ light year $= 5280$ ft
	$= 0.868$ mile (nautical)
1 foot (ft)	$= 30.480$ cm $= 1.894 \times 10^{-4}$ mi (statute)

Temperatures

Kelvin (absolute, °K) and centigrade (°C) scales:

$$T(°\mathrm{K}) = t(°\mathrm{C}) + 273.18$$

Centigrade and Fahrenheit (°F) scales:

$$t(°\mathrm{C}) = \tfrac{5}{9}[t'(°\mathrm{F}) - 32]$$

Energy Units

1 gram-calorie (gm-cal)	$= 4.186$ joules $= 3.968 \times 10^{-3}$ Btu
1 erg	$= 10^{-7}$ joule $= 2.3889 \times 10^{-8}$ gm-cal
	$= 1$ dyn-cm
1 joule	$= 10^{7}$ ergs $= 0.23889$ gm-cal
	$= 2.778 \times 10^{-7}$ kw-hr $= 1$ watt-sec
1 ev	$= 1.602 \times 10^{-12}$ erg

Figure 1.1 shows that the optical spectrum ranges in wavelength from about 0.1 cm, as the conventionally defined limit of the far infrared, to about 10^{-6} cm, at the short wavelength end of the ultraviolet. Since the experimentally significant extent of the electromagnetic spectrum covers more than 20 orders of magnitude in wavelength, one uses for convenience diversified units of length (see Table 1.1). The units important for the optical spectrum are the micron ($= 10^{-4}$ cm), the millimicron ($= 10^{-7}$ cm), and the angstrom ($= 10^{-8}$ cm). It is sometimes convenient to represent the electromagnetic spectrum in steps of octaves (viz., intervals in which the frequency and wavelength vary by a factor of two). The visible spectrum, then, spans about one octave, viz., 0.38–0.75 micron, the ultraviolet five, and the infrared about ten octaves. Furthermore, it has been the practice to subdivide the ultraviolet and infrared regions each into three parts, such as "near," "intermediate," and "far" infrared, as indicated in Fig. 1.1. These distinctions were originally made because of differences in techniques and phenomena; however, as more is learned about the various processes, their applicability is broadened beyond the initial limits, and the subdivisions become less meaningful. In fact, for the same reasons, the domain of the far infrared is already partially overlapped by that accessible to the generation of microwaves. A similar situation exists near 100 Å where the same region is claimed by x rays and the extreme ultraviolet. In such cases, the radiation is usually named for the method of its generation.

1.1.4 MODERN OPTICS

To the extent of the validity of Maxwell's equations, the phenomena of classical optics remain unchanged throughout the spectrum. In other words, if the linear dimensions of the apparatus (e.g., slits, gratings, mirrors) are scaled in constant proportion to the wavelength, such effects as interference and diffraction remain invariant with the spectral region. Conversely, if the size of the structure is fixed, such as in atoms and molecules, the effect on incident electromagnetic waves will depend qualitatively and quantitatively on wavelength. For this reason, interaction phenomena between radiation and matter are, in general, spectrally selective. The sixteen octaves of the optical spectrum affect matter in different ways, and the possible combinations with various materials give rise to a multitude of effects. Clearly, these phenomena reveal as much or more about the state of matter as they do about the nature of radiation and radiative interactions. This, then, is the subject of modern optics which had its beginning in the latter part of the nineteenth century.

Using the tools of radiometry and spectroscopy, the new approach moved quickly into a pivotal position for the development of physics: the discovery of the quantized nature of energy (Planck, 1900, and Einstein, 1905); the theory of atom structure and spectral lines (Bohr, 1914); the theory of the periodic system (Bohr, 1921); the exclusion principle for the spinning electron (Pauli, 1926); Raman effect (1928) and the understanding of the molecular bond; all these were results due to the exploration of matter by its emitted or absorbed light. More recently, the finer features of the radiation phenomena in excited gases and plasmas were brought into focus. Measurements of emission, absorption, and dispersion with instruments, often of high spectral resolution, were used to determine the dynamics between light and atoms, viz., the energy distribution, lifetimes, and transition probabilities. This area of modern optics is properly called *optical physics*, the name implying the study of interaction phenomena between optical radiation and matter. The field now includes in equal measure the phenomena occuring in solids, either intrinsically or owing to the presence of impurities. There are topics which lie at the outer fringes of this field, in which interest is centered, not on the radiation phenomena as such, but on the energy structure of a given material such as a superconductor. However, quite often such studies lead to the discovery of new means of detecting or exploring the radiation itself, and so both fields grow in cooperative fashion.

1.1.5 Applications

It is not our purpose to describe in detail the enormous number of applications which follow from the basic science of classical and modern optics and which, in fact, continue to be in a state of development. The field of geometrical optics, for example, aside from continuous improvements of instruments invented long ago, is forever surprising us with new ideas, methods, and systems, such as the new art of fiber optics. Again, multiple-beam interferometry is used to image and control submicroscopic surface irregularities by comparing them with the wavelength of light or rather with fractions thereof; in turn, the capabilities of physical optics are steadily advanced by the improvements of surface quality which it made possible. Although we shall briefly discuss the sources of radiation in the various wavelength regions, we shall not dwell on extraneous applications: the therapeutical and diagnostic value of ultraviolet and infrared; the use of infrared for power purposes such as drying; or even the application of spectroscopy to chemical analysis. What does concern us, however, are specific applications of modern optics, namely, those which are the exclusive domain of this field and which have been apt in the past to stimulate its fundamental study. Here belong such practical developments as line-sources or plasma radiators, masers and other sources of coherent radiation, and the vast field of photoelectric, photoconductive, and other means for the detection of radiation. In short, our concern is the generation, propagation, and detection of optical radiation and the physical processes on which the art is based.

1.2 Classical Model of Structure and Radiation

It has been brought out in the introduction that the subject of our treatise is largely the interaction between optical radiation and matter. The procedure that we shall follow is to first describe basic concepts of what constitutes matter, insofar as it affects radiation, and then develop in detail the connection with optical processes. Thus we shall deal with the physical models accounting for the origin of optical radiation; the phenomena associated with its propagation through a medium, viz., reflection, refraction, scattering, polarization, etc.; and the processes responsible for absorption, viewing these either as the inverse of the generation processes, or as mechanisms of attenuation, or as the phenomena used in detection. The media with which these interactions occur will be mainly solid or gaseous. The optics of the liquid state has few aspects which are different from either that of solids or that of gases, and their practical significance is relatively small. Important and common to all these interactions are the following considerations.

Almost by definition, at least within the scope of our subject, electromagnetic radiation interacts with matter only through the electric charges which make up matter, or more accurately, through the motion of such charges. This may be only indirectly accounted for, or implicitly described, in the physical models and quantitative relations of which the theory of electromagnetism consists. As an example, the theory of metal optics relates such parameters as reflectance and absorptance to conductivity, dielectric constant, and permeability, through which the role of atomic charges is only indirectly represented. It is, then, in the last analysis, electrons and ions which individually or cooperatively interact with electromagnetic fields in the phenomena of radiation.

Now the various types of structural bonds which link charges together, thereby determining the properties of matter, comprise also the most important factor in determining what kind of interaction can occur with radiation and at what frequencies the phenomenon takes place. In other