Optics

Second Edition

OPTICS
Second Edition

Sir Francis Graham Smith F.R.S.

J. H. Thomson

Department of Physics,
University of Manchester

John Wiley & Sons Ltd.

CHICHESTER NEW YORK BRISBANE TORONTO SINGAPORE

Library of Congress Cataloging in Publication Data:

Smith, F. Graham (Francis Graham), 1923-
Optics/F. Graham Smith, J H Thomson — 2nd ed
p. cm. — (The Manchester physics series)
Bibliography p
Includes index
ISBN 0 471 91534 3 ISBN 0 471 91535 1 (pbk.)
1. Optics. I Thomson, J H. (John Hunter) II. Title.
III. Series.
QC355.2.S55 1988 87-22174
535 — dc19 CIP

British Library Cataloguing in Publication Data:

Smith, F. Graham
Optics. — 2nd ed — (The Manchester physics series)
1. Optics
I. Title II Thomson, J H III Series
535 QC355 2

ISBN 0 471 91534 3
ISBN 0 471 91535 1 Pbk

Phototypeset by Dobbie Typesetting Service, Plymouth, Devon
Printed by St Edmundsbury Press, Bury St Edmunds Suffolk

The Manchester Physics Series

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Editors' Preface to the Manchester Physics Series

The first book in the Manchester Physics Series, *Properties of Matter*, was published in 1970. Since then, eight volumes have appeared in the series and we have been extremely encouraged by the response of readers, both colleagues and students. These books have been reprinted many times and are being used world-wide in the English language edition and in translations. All the same, both the editors and authors feel the time is right for a revision of some of the books in order to take into account the feedback received and to reflect the changing style and needs of undergraduate courses.

The Manchester Physics Series is a series of textbooks on physics at undergraduate level. It grew out of our experience at Manchester University Physics Department, widely shared elsewhere, that many textbooks contain much more material than can be accommodated in a typical undergraduate course and that this material is only rarely so arranged as to allow the definition of a shorter self-contained course. In planning these books, we have had two objectives. One was to produce short books: so that lecturers should find them attractive for undergraduate courses; and so that students should not be frightened off by their encyclopaedic size or their price. To achieve this, we have been very selective in the choice of topics, with the emphasis on the basic physics together with some instructive, stimulating and useful applications. Our second aim was to produce books which allow courses of different length and difficulty to be selected, with emphasis on different applications. To achieve such flexibility we have encouraged authors to use flow diagrams showing the logical connections between different chapters and to put some topics in starred sections. These cover more advanced and alternative material which is not required for the understanding of later parts of each volume.

Although these books were conceived as a series, each of them is self-contained and can be used independently of the others. Several of them are suitable for use outside physics courses; for example, *Electronics* is used by electronic engineers, *Properties of Matter* by chemists and metallurgists. Each author's preface gives details about the level, prerequisites, etc., of the particular volume.

We are extremely grateful to the many students and colleagues, at Manchester and elsewhere, whose helpful criticisms and stimulating comments have led to many improvements. Our particular thanks go to the authors for all the work they have done, for the many new ideas they have contributed, and for discussing patiently, and often accepting, our many suggestions and requests. We would also like to thank the publishers, John Wiley & Sons, who have been most helpful.

January, 1987

F. MANDL
R. J. ELLISON
D. J. SANDIFORD

Author's Preface

This book is based on wave concepts, and includes a thorough introduction to the physics of wave motion. There are major changes from the original first edition. We now introduce Fourier theory at an early stage, so that reference can be made to it throughout the book, greatly simplifying much of the later material. New material on modern optics has been included, and peripheral material on vibrations has been omitted.

The basic concepts of geometric optics, and of interference and diffraction, are presented in a sufficiently concise form to allow room for several developments in modern optics, and for the description of practical spectrometers and interferometers. Later chapters provide an introduction to lasers, holography, and to the generation and detection of light. Much of this material has been re-written to take account of developments in the last fifteen years. Physical concepts are emphasized throughout, so that optics can be seen in relation to other disciplines such as electricity and atomic physics.

The first sixteen chapters form a conventional course, which branches into several independent topics in later chapters. Geometric optics is treated by wave concepts; it forms an independent section which may be omitted without loss of continuity. Sections marked with a star may also be omitted on first reading. A flow diagram is included on the inside cover.

The number of examples has been considerably increased: these are now found at the end of the first fifteen chapters, and numerical answers and notes are collected together near the end of the book.

It is sad for me to record that my friend and colleague, John Thomson, died before this book was completed. Although much of his work remains, I have to take full responsibility for this second edition. Dr John Ellison provided invaluable suggestions for the major reorganization and improvement of the text.

F. GRAHAM SMITH

Contents

★ Starred sections may be omitted as they are not required later in the book.

CHAPTER 1

The wave nature of light

1.1 PHOTONS AND WAVES

Optics in the days of Newton was a branch of physics which was clearly defined and separate from mechanics, heat, electricity, and magnetism. Today it is a subject which acts as a bridge, bringing together concepts from all other parts of physics, and linking closely with such diverse subjects as the engineering of communications and high-energy nuclear physics. The link is the wave nature of light.

The behaviour of light waves is typical of the wide range of waves known as electromagnetic waves. Light occupies a place in the electromagnetic spectrum intermediate between the long radio waves, which we are accustomed to think of as oscillating and propagating electric fields, and the short X-rays and gamma rays, which we think of as energetic particles. The whole of this range is in fact governed by the same basic laws, and the whole of our study of light will be found to apply in some way to other parts of the spectrum. The differences of behaviour are, however, very large. The frequencies of the oscillations vary from 10^4 Hz for long radio waves to more than 10^{21} Hz for gamma rays (1 Hertz equals one cycle per second), and the wavelengths from 30 km to less than 1 picometre ('pico' = 10^{-12}). Radio waves are generated and detected as an oscillating electric or magnetic field, and it is unusual (but not unknown) to hear a physicist refer to a quantum process in the radio frequency spectrum. Gamma rays are packets of energy, photons, emitted and absorbed in atomic and nuclear reactions: only rarely will a physicist refer to a frequency of a gamma ray, but he will instead refer to its energy.

The laws governing the propagation of electromagnetic waves are the same for all wavelengths; some are sufficiently general to apply equally to many other quite different kinds of waves. The quantum nature of a wave, which is responsible for the obvious differences between a gamma ray and a radio wave, is only revealed when waves and matter interact. Waves are found to exchange energy and momentum with their generators and absorbers only in discrete packets, according to quantum laws. These discrete packets of energy, the quanta, are photons. They need not be considered to exist at all during the propagation of a wave, but only as a limitation on the possible ways in which radiation interacts with matter. The relation of the size of the quantum to common levels of energy in matter determines the relative importance of the quantum at different parts of the spectrum: gamma-rays, with a high photon energy and a high photon momentum, can act on matter explosively or like a high-velocity billiard ball, while long infrared or radio waves, with a low photon energy, do not interact so much with individual atoms as with matter on a larger scale, through classical electric and magnetic induction.

The photon energy of light waves is such that quantum effects dominate only some of the processes of emission and reception. The visible spectrum contains the marks of quantum processes in the profusion of colour from line emission and absorption, but it also can display a continuum of emission over a wide range of wavelengths, giving 'white' light, whose actual colour is determined by the large-scale structure of the continuum spectrum rather than its fine detail.

The wavelength of visible light is at the same time sufficiently short for us to observe effectively rectilinear propagation, as though light were propagated as a stream of particles, and long enough for us to observe easily many interference and diffraction effects with apparatus whose dimensions are in some way commensurate with the wavelength. We find therefore in the study of light most of the physical phenomena of electromagnetic waves, and although we may refer to other wavelengths for illustration, light provides our main examples of the propagation, interference, and diffraction of waves, the main themes of this book. Photons are referred to only briefly, in Chapters 17 and 19 on the generation and Chapter 21 on the detection of light; from our point of view a photon does not exist except in a transfer of energy and momentum to or from the electromagnetic field, and we do not therefore describe light as a stream of photons, or speculate about the interference of one photon with another. It is wave propagation we are dealing with, and we start therefore with a general study of waves.