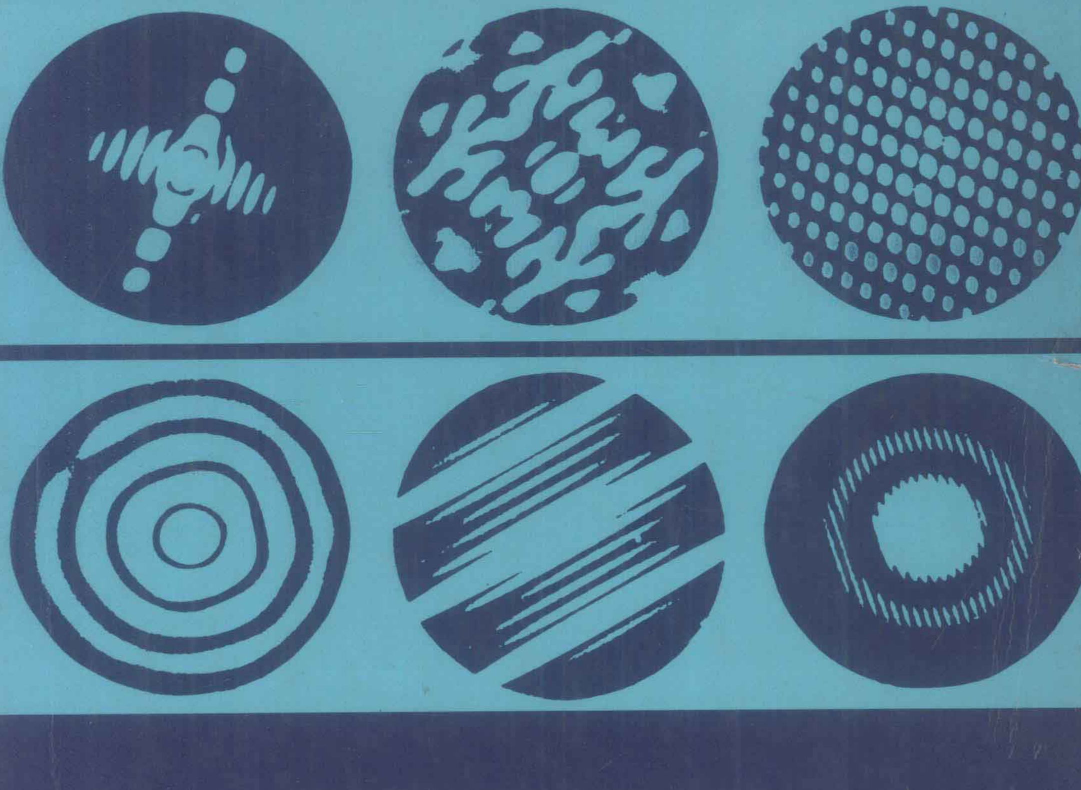
OPTICAL PHYSICS

S.G. LIPSON & H. LIPSON



SECOND EDITION

OPTICAL PHYSICS

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OPTICAL PHYSICS

To my mother
S. G. L.

To my wife
H. L.

Preface to the second edition

Since the writing of the first edition the subject of Optics, as studied in universities, has grown greatly both in popularity and scope, and both we and the publishers thought that the time had arrived for a new edition of *Optical Physics.*

In preparing the new edition we have made substantial changes in several directions. First, we have attempted to correct all the mistakes and misconceptions that have been pointed out to us during the nine years the book has been in use. Secondly, we have made one important change in the subject matter: we have absorbed the chapter on Quantum Optics into the rest of the book. During the years, there have appeared many books devoted to laser physics, and it now seems impracticable for a book on physical optics to cover the subject at all satisfactorily in one chapter. However, since some knowledge of the principles of the laser is necessary for the understanding of physical optics today, particularly when coherence is being discussed, we have covered what we feel to be the necessary minimum as parts of Chapters 7 and 8.

In addition to the above changes in the subject matter, we have increased the number of exercises offered to the reader, organized them according to chapter, and provided solutions. We have also included a few suggestions, based on our experience, for student projects illustrating the material in the book.

We are, of course, most grateful to all those who have pointed out to us errors and room for improvement. But in particular we must thank D. S. Tannhauser, I. Senitsky and M. Neugarten who have helped us considerably by reading and criticizing in detail parts of the revised manuscript. We are also extremely grateful to the staff of Cambridge University Press, who have contributed considerably to the elimination of faults and inaccuracies in our manuscript.

S. G. Lipson

May 1979 H. Lipson

Preface to the first edition

There are two sorts of textbooks. On the one hand, there are works of reference to which students can turn for the clarification of some obscure point or for the intimate details of some important experiment. On the other hand, there are explanatory books which deal mainly with principles and which help in the understanding of the first type.

We have tried to produce a textbook of the second sort. It deals essentially with the principles of optics, but wherever possible we have emphasized the relevance of these principles to other branches of physics – hence the rather unusual title. We have omitted descriptions of many of the classical experiments in optics – such as Foucault's determination of the velocity of light – because they are now dealt with excellently in most school textbooks. In addition, we have tried not to duplicate approaches, and since we think that the graphical approach to Fraunhofer interference and diffraction problems is entirely covered by the complex-wave approach, we have not introduced the former.

For these reasons, it will be seen that the book will not serve as an introductory textbook, but we hope that it will be useful to university students at all levels. The earlier chapters are reasonably elementary, and it is hoped that by the time those chapters which involve a knowledge of vector calculus and complex-number theory are reached, the student will have acquired the necessary mathematics.

The use of Fourier series is emphasized; in particular, the Fourier transform – which plays such an important part in so many branches of physics – is treated in considerable detail. In addition, we have given some prominence – both theoretical and experimental – to the operation of convolution, with which we think that every physicist should be conversant.

We would like to thank the considerable number of people who have helped to put this book into shape. Professor C. A. Taylor and Professor A. B. Pippard had considerable influence upon its final shape – perhaps

more than they realize. Dr I. G. Edmunds and Mr T. Ashworth have read through the complete text, and it is thanks to them that the inconsistencies are not more numerous than they are. (We cannot believe that they are zero!) Dr G. L. Squires and Mr T. Blaney have given us some helpful advice about particular parts of the book. Mr F. Kirkman and his assistants – Mr A. Pennington and Mr R. McQuade – have shown exemplary patience in producing some of our more exacting photographic illustrations, and in providing beautifully finished prints for the press. Mr L. Spero gave us considerable help in putting the finishing touches to our manuscript.

And finally we should like to thank the three ladies who produced the final manuscript for the press – Miss M. Allen, Mrs E. Midgley and Mrs K. Beanland. They have shown extreme forbearance in tolerating our last-minute changes, and their ready help has done much to lighten our work.

S.G.L.
H.L.

Contents

1

History of ideas

1.1 Importance of history

Why should a textbook on physics begin with history? Why not start with what is known now and refrain from all the distractions of out-of-date material? These questions would be justifiable if physics were a complete and finished subject; only the final state would then matter and the process of arrival at this state would be irrelevant. But physics is not such a subject, and optics in particular is very much alive and constantly changing. It is important for the student to understand the past as a guide to the future. To study only the present is equivalent to trying to draw a graph with only one point.

Moreover, by studying the past we can sometimes gain some insight – however slight – into the minds and methods of the great physicists. No textbook can, of course, reconstruct completely the workings of these minds, but even to glimpse some of the difficulties that they overcame is worthwhile. What seemed great problems to them may seem trivial to us merely because we now have generations of experience to guide us; or, more likely, we have hidden them by cloaking them with words. For example, to the end of his life Newton found the idea of 'action at a distance' repugnant in spite of the great use that he made of it; we now accept it as natural, but have we come any nearer than Newton to understanding it? By being brought back occasionally to such fundamental problems the physicist is bound to have his wits sharpened; no amount of modern knowledge can produce the same effect. The way to study physics is to ask questions, as the geniuses of the past asked them. The ordinary physics student will find someone to answer them; the good physics student will answer them himself.

1.2 The nature of light

1.2.1 *The first ideas.* Some odd ideas about the nature of light were put forward by the ancients, who wanted the sense of sight to be somehow similar to the sense that they knew best – that of touch. But this idea did not make much headway, and it was not until Galileo (1564–1642) introduced the experimental method that progress really began. Galileo was the first scientist effectively to propagate the idea of testing theories by experiment and, as an example, he tried to measure the speed of light. He failed, but even to have thought of the concept was an intellectual triumph.

1.2.2 *The basic facts.* What was known about light in the seventeenth century? First of all, it travelled in straight lines. Secondly, it was reflected off smooth surfaces and the laws of reflexion were known. Thirdly, it changed direction when it passed from one medium to another (refraction); the laws for this phenomenon were not so obvious, but by the year 1600 they had been established by Snell (1591–1626) and were later confirmed by Descartes (1596–1650). Fourthly, what we now call Fresnel diffraction had been discovered by Grimaldi (1618–63) and by Hooke (1635–1703). Finally, double refraction had been discovered by Bartholinus (1625–98). It was on the basis of these phenomena that a theory of light had to be constructed.

The last two facts were particularly puzzling. Why did shadows reach a limiting sharpness as the size of the source became small, and why did fringes appear on the light side of the shadow (Fresnel diffraction)? And why did light passing through a crystal of Iceland spar produce two images when light passing through most other transparent materials produced only one?

1.2.3 *The wave–corpuscle controversy.* As usual in science when there is inadequate evidence, controversy resulted. Newton threw his authority on the theory that light is corpuscular, mainly because his first law of motion said that if no force acts on a particle it will travel in a straight line; he therefore postulated that light corpuscles are not acted upon by ordinary forces such as gravity. Double refraction he explained by some asymmetry in the corpuscles, so that their directions depended upon whether they passed through the crystal forwards or sideways. He envisaged the corpuscles as resembling magnets and the word 'polarization' is still used (Chapter 5) although this explanation has long been discarded.

Diffraction, however, was difficult. Newton realized its importance and carried out some crucial experiments in the subject; he showed that the fringes formed in red light were separated more than those formed in blue light. But when he found that the corpuscular theory could not be made to fit in, he weakly dropped his experiments, saying that he was rather busy!

Newton was also puzzled by the fact that light was partly transmitted and partly reflected by a glass surface; how could his corpuscles sometimes go through and sometimes be reflected? He answered this question by propounding the idea of 'fits of reflexion' and 'fits of transmission'; in a train of corpuscles some would go one way and some the other. He even worked out the lengths of these 'fits' (which came close to what we now know as half the wavelength). But the idea was very cumbersome and was not really satisfying.

His opponent, Huygens (1629–95) was a supporter of the wave theory. With it he could account for diffraction and for the behaviour of two sets of waves in a crystal, without explaining *how* the two sets arose. Both he and Newton had a common misconception – that light waves, if they existed, must be like sound waves, which are longitudinal. It is surprising that the two greatest minds in science should have had this blind spot. If they had thought of transverse waves, the difficulties of explaining double refraction would have disappeared.

1.2.4 *Triumph of wave theory.* Newton's authority kept the corpuscular theory going until the end of the eighteenth century, but by then ideas were coming forward that could not be suppressed. In 1801 Young (1773–1829) produced his double-slit fringes (Fig. 1.1) – an experiment

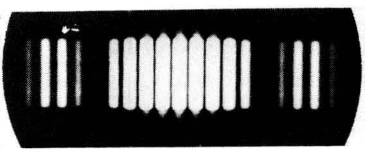

Fig. 1.1. Young's fringes.

so simple to carry out and so simple to interpret that the results were incontrovertible; in 1815 Fresnel (1788–1827) worked out the theory of the Grimaldi–Hooke fringes; and in 1821 Fraunhofer (1787–1826) produced diffraction patterns in parallel light which were much more amenable to theoretical treatment than were the Grimaldi–Hooke fringes. These three men laid the foundation of the wave theory that is still the basis of what is now called physical optics.

Nevertheless the corpuscularists were not quite defeated. In 1818 Poisson (1781–1840) produced an argument that seemed to invalidate the wave theory; he used the device of *reductio ad absurdum.* Suppose that a shadow of a perfectly round object is cast by a point source: at the periphery all the waves will be in phase, and therefore the waves should also be in phase at the centre of the shadow; there should therefore be a bright spot at this point. Absurd! Fresnel and Arago (1786–1853) carried out the experiment and found that there really *was* a bright spot at the centre (Fig. 1.2). Users of *reductio ad absurdum* should make sure of the absurdity of the result they are criticizing.

The triumph of the wave theory seemed complete.

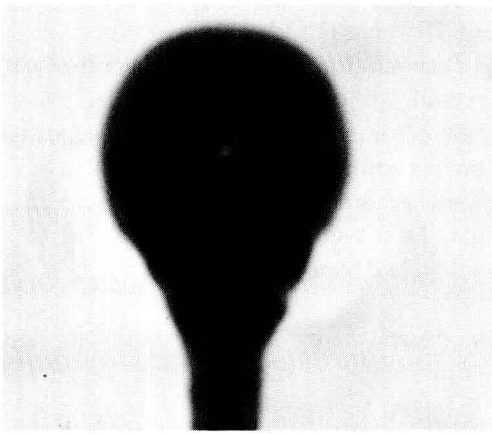

Fig. 1.2. The bright spot at the centre of the shadow of a disc.

1.3 Speed of light

1.3.1 *Measurement.* The methods that Galileo used to measure the speed of light were far too crude to be successful. In 1678 Römer (1644–1710) realized that an anomaly in the times of successive eclipses of the moons of Jupiter could be accounted for by a finite speed of light, and deduced that it must be about 3×10^8 m s^{-1}. In 1726 Bradley (1693–1762) made the same deduction from observations of the small ellipses that the stars describe in the heavens; since these ellipses have a period of one year they must be associated with the movement of the Earth.

It was not, however, until 1850 that direct measurements were made, by Fizeau (1819–96) and Foucault (1819–68); their experiments are fully described in elementary textbooks, and their results confirmed those of Römer and Bradley. In the hands of Michelson (1852–1931) their methods achieved a high degree of accuracy – about 0.03 per cent. This, then, was one important problem completely disposed of.

1.3.2 *Refractive index.* Foucault's method was the more versatile in that it required a relatively short path, and the speed of light could be measured in media other than air – water, for example. This enabled another important result to be obtained. According to the corpuscular theory (§ 1.2.3) the speed of light should be greater in water than in air because the corpuscles must be attracted towards the water to account for the changed direction of the refracted light; according to the wave theory, the waves must travel more slowly in water and 'slew' round to give the new direction (Fig. 1.3). Foucault's method confirmed the wave theory completely, but of course gave no indication of the nature of the waves.

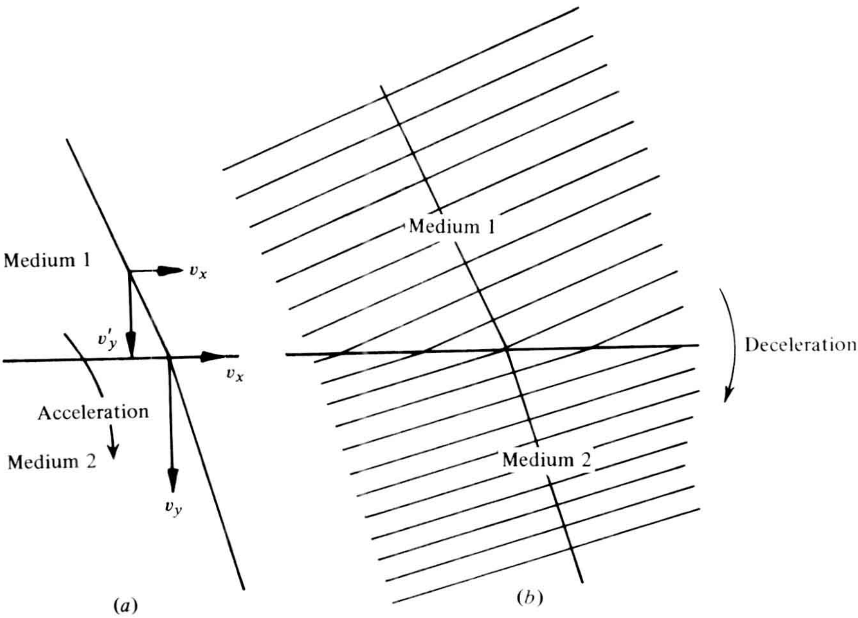

Fig. 1.3. (*a*) Refraction according to the corpuscular theory; (*b*) Refraction according to the wave theory.

1.4 Transverse or longitudinal waves?

1.4.1 *Polarization.* The distinction between transverse and longitudinal waves had been appreciated early in the history of physics; sound waves were found to be longitudinal and water waves were obviously transverse.

The phenomenon that enabled a decision to be made was that of double refraction in Iceland spar (§ 1.2.2). Huygens pointed out that this property, which is illustrated in Fig. 1.4, must mean that the orientation of the crystal must be related somehow to some direction in the wave.

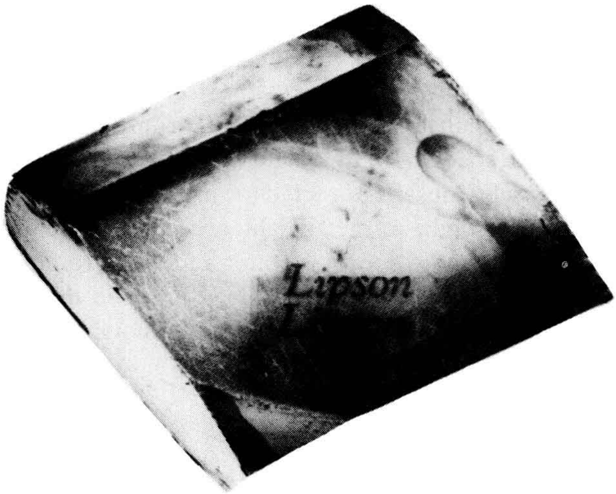

Fig. 1.4. Double refraction in an Iceland spar crystal.

We now know that this is the correct solution. We shall discuss the results of these ideas in more detail in Chapter 4.

1.4.2 *Nature of light.* These experiments, of course, tell us nothing about the nature of light; they are all concerned with its behaviour. The greatest step towards understanding came from a completely different direction – the theoretical study of magnetism and electricity.

In the first half of the nineteenth century the relationship between magnetism and electricity had been worked out fairly thoroughly, by men such as Oersted (1777–1851), Ampère (1775–1836) and Faraday (1791–1867). In 1864 Clerk Maxwell (1831–79) was inspired to put their results in mathematical form, and in manipulating the equations he found that they could assume the form of a wave equation. The velocity of the wave could be derived from the known magnetic and electric constants. Evaluation of this velocity showed that it was equal to the velocity of light, and thus light was established as an electromagnetic disturbance. This was one of the most brilliant episodes in physics, bringing together several different branches of physics and showing their relationship to each other.

1.5 Instruments

1.5.1 *The telescope.* Although single lenses had been known from time immemorial, it was not until the beginning of the seventeenth century