IOP Concise Physics

Optics
The science of light
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Chapter 1

Introduction and structure of the course

The study of light has been an important part of science from its beginning. From early times optics has been instrumental for the technology of measurement. Eratosthenes (276–194 BC) famously measured the circumference of the Earth using the length of shadows cast by a vertical rod at two distant points on a north–south line in what is modern-day Egypt[1]. He correctly assumed that the Sun was sufficiently distant that its rays would be parallel at the Earth's surface and that the light travelled in straight lines. This principle, that light travels in straight lines, was first articulated by Heron of Alexandria (c. 10–75 AD) but has come to be known as Fermat's Principle and underlies what we call geometrical optics. Later, Islamic scholars made significant contributions with Alhazen (Ibn al-Haytham, b. 965 AD), in particular, demonstrating this rectilinear propagation of light and performing experiments using lenses and mirrors to study refraction and reflection. Medieval philosophers built on the writings of both Greek and Arabic scholars with Roger Bacon (1219–1292) working in Oxford and Paris making quantitative studies of refraction at spherical surfaces, following the path of light through lenses and, in some sense, foreseeing the operation of the telescope. With the coming of the Scientific Revolution in the 16th and 17th centuries, optics, in the shape of telescopes and microscopes, provided the means to study the Universe from the very distant to the very small. Isaac Newton (1642–1726) introduced a scientific study also of the nature of light itself, considering it to be composed of a stream of tiny 'corpuscles' or particles rather than some form of wave as suggested previously by Christiaan Huygens (1629–1695). Subsequently, this particle-picture was replaced by the wave theory supported, in particular, by the experimental observations by Thomas Young (1773–1829) and mathematical formulations by Augustin-Jean Fresnel (1788–1827)

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[1] He obtained a value of 250 000 stadia but, sadly, since we are not certain how his unit of length, stadia, corresponds to one metre, we can't be sure how accurate his measurement was, but it was probably correct to within about 20%.

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and others. The triumph of wave theory was seemingly sealed by James Clerk Maxwell (1831–1879) whose theory unified electricity and magnetism and indicated light to be composed of waves in the electromagnetic field. The dominance of the wave theory of light was short-lived. In 1921 Albert Einstein (1879–1955) was awarded the Nobel Prize in Physics partly for his explanation of the photo-electric effect in terms of essentially a ‘particle-picture,’ whereby light was composed of discrete quanta, or photons, containing a definite amount of energy. This quantum idea was consistent with the law discovered earlier by Max Planck (1858–1947) relating the energy of radiation to its frequency in discrete units. Planck’s discovery explained the distribution of spectral energy radiated by ‘black bodies’, especially in the ultra-violet region, where classical electromagnetic theory had catastrophically failed.

Today, optics remains a key element of modern science, not only as an enabling technology, but in quantum optics, as a means of testing our fundamental understanding of quantum theory and the nature of reality itself. Since the establishment of the quantum theory of light, it is often stated that light behaves sometimes as a wave and sometimes as a particle. Arguably, a more correct view is that light is neither a wave nor a particle but better considered as a quantum entity that displays ‘wave-like’ or ‘particle-like’ properties depending on the method of detection. The ‘real’ nature of light remains, to some extent, an intriguing mystery!

In what follows we will be concerned principally with the wave nature of light. Most experimental studies of light will involve optical elements such as lenses and mirrors and so an understanding of how they work will be useful. We will therefore begin with a very brief summary of some relevant geometrical optics in chapter 2, which ignores the wave nature of light. We will, however, return later to see how the wave nature affects the performance of some important optical instruments.

The main focus of the book is physical optics where the primary characteristic of waves viz *interference*, is the dominant theme. It is interference that causes diffraction—the bending of light around obstacles. Our study of how waves behave will rely on having a clear mathematical description of wave phenomena and so this is introduced in chapter 3 together with a brief résumé of elementary diffraction effects. The basics of scalar diffraction theory and Fraunhofer diffraction are then introduced in chapter 4. By using a scalar theory we ignore the vector nature of the electric field of the wave, but we return to this aspect at the end of the course when we think about the polarization of light. Scalar diffraction theory allows us to mathematically treat the propagation of light and the effects of obstructions or restrictive apertures in its path. We then introduce, in chapter 5, a very powerful mathematical tool, the Fourier transform, and show how this can help in solving difficult diffraction problems. Fourier methods are used very widely in physics and recognise the inter-relation of variables in different dimensions such as ‘time and frequency’ or ‘space and spatial frequency’. The latter concept will be useful to us in understanding the formation of images in optical systems.

Having established the mathematical basis for describing light we turn to methods of analysing the spectral content of light. The spectrum of light is the primary link between optics and atomic physics and other sciences such as astrophysics. The basis for almost all instruments for spectral analysis is, again, interference and so in chapter 6 we look at the physics underlying the formation of the interference patterns in various types of instrument. The familiar Young's slit, two-beam, interference effect in which the interference arises from division of the wavefront is generalised to multiple slits in the diffraction grating spectrometer and this is treated in chapter 7. The alternative method of producing interference, by division of amplitude, is then considered in chapter 8 where, again, we begin with the case of two beams: the Michelson interferometer and move on, in chapter 9, to multiple-beam interference in the Fabry–Pérot interferometer. These devices are important tools and play a key role in modern laser physics and quantum optics. The reflection and transmission of light at boundaries between dielectric media is an important feature of almost all optical instruments and so we then consider, in chapter 10, how the physics of wave reflection at boundaries can be engineered to produce surfaces with high or partial reflectivity or even no reflectivity at all. Finally, in chapter 11, we return to the vector nature of the electric field in the light wave. The direction in which the E-field points defines the polarization and we will study how to produce, manipulate and analyse the state of polarization of light.