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Photonics – An Introduction

Photonics is probably the outstanding candidate for the principal enabling technology of the twenty-first century. The term emerged around half a century ago and is now slowly creeping into everyday vocabulary just as ‘electronics’ did in the twentieth century. The aim in this short book is to introduce the principal concepts and ideas which underpin photonics and to explore its current and evolving technological significance.

1.1 What is Photonics?

‘Photonics is the science of light. It is the technology of generating, controlling and detecting lightwaves and photons, which are particles of light. The characteristics of the waves and photons can be used to explore the universe, cure diseases and even to solve crimes. Scientists have been studying light for hundreds of years. The colours of the rainbow are only a small part of the entire lightwave range called the electromagnetic spectrum. Photonics explores a wider variety of wavelengths, from gamma rays to radio including X-rays, ultraviolet and infrared light.’ This succinct definition comes from the website of the International Year of Light (IYL) celebrated in 2015.

The concepts through which we explore and understand light are indeed common throughout the electromagnetic wave spectrum, as indicated in the IYL definition. However, it is straightforward to appreciate that the scale of the wavelengths across this spectrum, extending from hundreds of metres for radio waves to subnanometres at X-ray frequencies, implies that different features within this common set will become more or less dominant in the understanding and application of a particular part of the spectrum. The transition from ‘electronics’ to ‘photonics’ reflects this gradual transfer, as indicated in Figure 1.1.

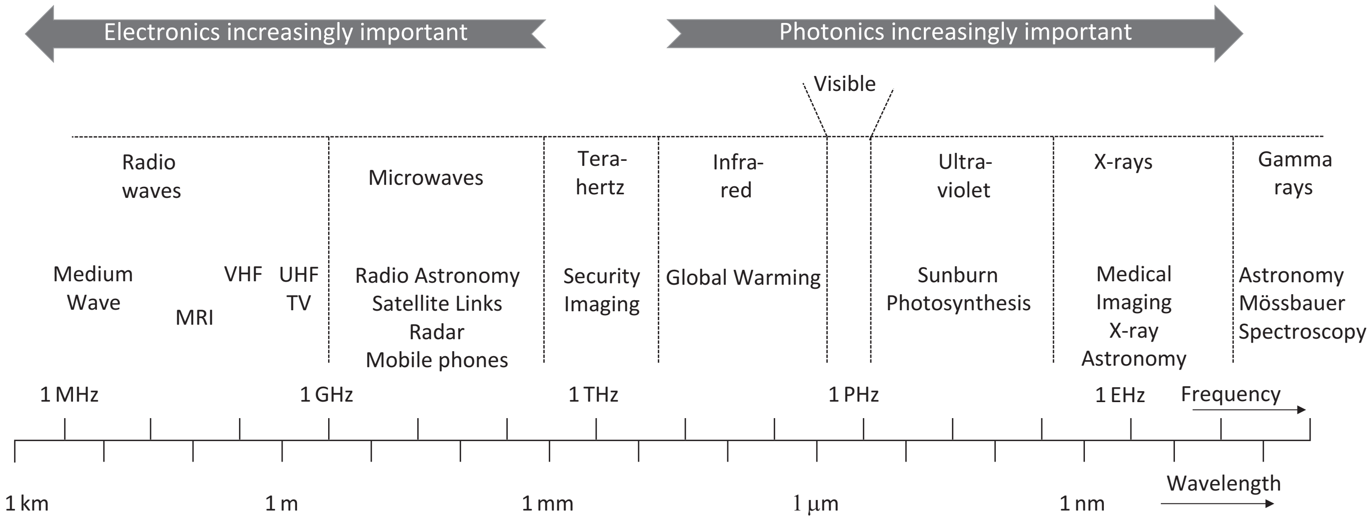

Figure 1.1 The principal regions of the electromagnetic spectrum. The boundaries between the various regions are fuzzy (except for the tiny visible part), though most regions have a presence in everyday life.

The focus in what follows is on those concepts which are most important in and around the visible spectrum, from the far infrared to the far ultraviolet. This has emerged as the more conventional domain for the term 'photonics'. The aspiration in this book is to convey an intuitive understanding of the essential photonics concepts and to develop a critical insight into applying them in order to appreciate the potential and, indeed, the limitations of new and emerging photonic technologies.

1.2 Exploring Some Concepts

The basic ideas of electronics and of photonics concern the interactions between electromagnetic radiation and materials. These interactions in turn depend fundamentally on both the material itself and also its dimensions compared with the wavelength of the electromagnetic radiation (Figure 1.1). This is exemplified through the observation that television is broadcast on radio waves with ultra-high frequencies – a few hundred MHz – where the wavelength is around the dimensions of a domestic antenna. From the antenna the signal proceeds into an electronic circuit – in your TV – which 'holds' the arriving electromagnetic wave within its much smaller dimensions. There is also an intermediate phase, in which the electromagnetic wave captured by your TV antenna is trapped within a cable before arriving at the electronic circuit. The flow of electrons in materials is common to the whole process, since the transmitted TV wave is generated from electrons flowing through a suitable transforming device to produce a propagating electromagnetic wave.

The source of the term 'photonics' lies in the concept of the photon. Photons, discrete quanta of light, were inferred through the 'ultraviolet catastrophe' in the black body spectrum and later more clearly defined through Einstein's description of the photoelectric effect, in which electrons are emitted from a material only if sufficient energy is acquired from the incident light. The required energy depends not on the incident power but on the optical frequency. This is in contrast with what is happening in a TV antenna which modifies the movement of already free electrons in a way that is directly dependent on the total power. However, it was already known that in other structures, lightwaves behaved in exactly the same way as radio waves, for example in transmitting through the atmosphere, being reflected at dielectric boundaries or interfering with themselves after transmission through different paths.

In photonics the threshold of 'where photonics matters' is now associated with the energy of the photon. The term 'photonics' becomes applicable when the photon energy becomes comparable with or exceeds the thermal energy of the particles in the material with which the electromagnetic wave is interacting. The energy of the photon, namely Planck's constant multiplied by the frequency of the electromagnetic wave, and the energy of a freely moving particle, which is of the order of Boltzmann's constant times the absolute temperature, are compared in Figure 1.2 at a temperature of 300 K. (The photon energy here is presented in electron volts – the energy change as an electron changes its electrical potential by 1 V – see Appendix 5 for the values of these constants.) When the photon energy comfortably exceeds the inherent thermal background energy of particles (at a wavelength of about 30 microns at 300 K – the far infrared), then electromagnetic radiation is captured or, indeed, generated as a particle. At lower energies (wavelengths above about 300 microns, 1 THz) we can regard the capture or generation of electromagnetic radiation as being due to a flow of electrons produced by the electric field in an electromagnetic wave. In other words, at lower frequencies a wave model for the interaction becomes appropriate; the ideas of 'electronics' rather than 'photonics' apply. This will depend on temperature: at 3 K a photonic description of an interaction will begin to be applicable at frequencies two decades less than at 300 K.

Similar observations apply to structural dimensions, though the boundaries between the photonic and electronic descriptions are based on different criteria. Materials behave 'electronically' when their dimensions are significantly less

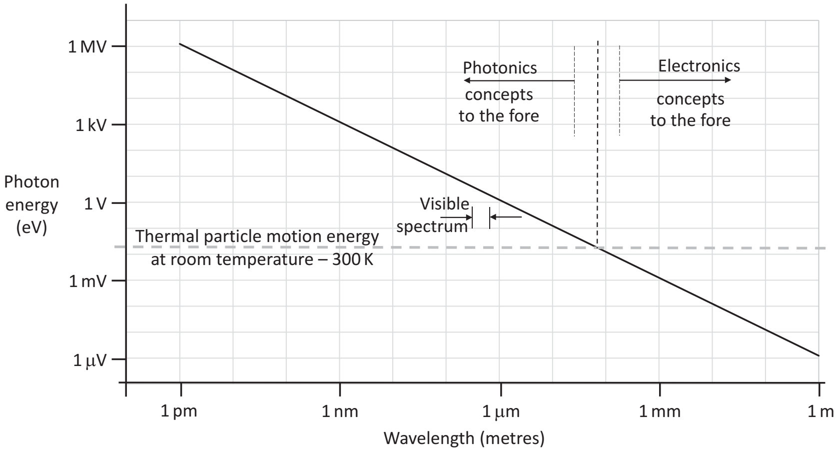

Figure 1.2 The plot shows photon energy as a function of wavelength. The broken line shows the energy of thermal random motion at 300 K. At wavelengths below about 30 microns (10 THz), the photon energy begins to dominate. At about 300 microns (~1 THz) the ideas of electronics become more applicable. The THz region falls in the transition zone.

than a wavelength. A contrasting aspect of photonics has been that very small scale structures with dimensions in the photonics region have only recently become potentially achievable; that is, to dimensional precision measured in nanometres. It is remarkable that gold nanospheres have been used to provide a spectrum of permanent colour in glassware since ancient times. Finally, there is the dimensional range of structures which is comparable with the wavelength and it is here that diffraction effects, in particular, become critically important and waveguiding – as in fibre optics – comes to the fore.

These principles and their context in potential applications will be explored in more detail later in the book. They have, however, prompted considerable debate as to whether light is 'really' a wave or a particle. The answer to this question is that it depends on the context. Our aspiration here is to help develop an understanding of which approach is relevant and when. An attempt to portray these differing situations is presented in Figure 1.3, which highlights the underlying phenomena that constitute photonics.

1.3 Applications

Applications, achieved and potentially feasible, are becoming a major stimulus for the interest in and development of photonics. We shall explore briefly a number of case studies later in the book, but among the everyday presence of photonics sits the internet, which could not function at all without fibre optic communications. Your camera, your smart phone and the increasing efficiency and versatility of lighting technologies all rely on recent advances in photonics. Many aspects of medical diagnosis, microscopy and medical therapeutics, rely on photonics. Optical absorption is the initiator for climate change; the monitoring processes measuring changes in our atmosphere, as well as the long-term solutions aimed at driving our energy sources directly from light, all need an understanding of photonics and its exploitation.

1.4 About This Book

The essential concepts which are covered in the book are shown in Figure 1.4. The next three chapters are devoted to the principles of the subject. Having established the principles, we shall explore some current applications through brief case studies. Finally comes a speculative look at the future in terms of both the enabling technologies and the technological advantages, together with some social needs to which photonics may contribute to in the future either

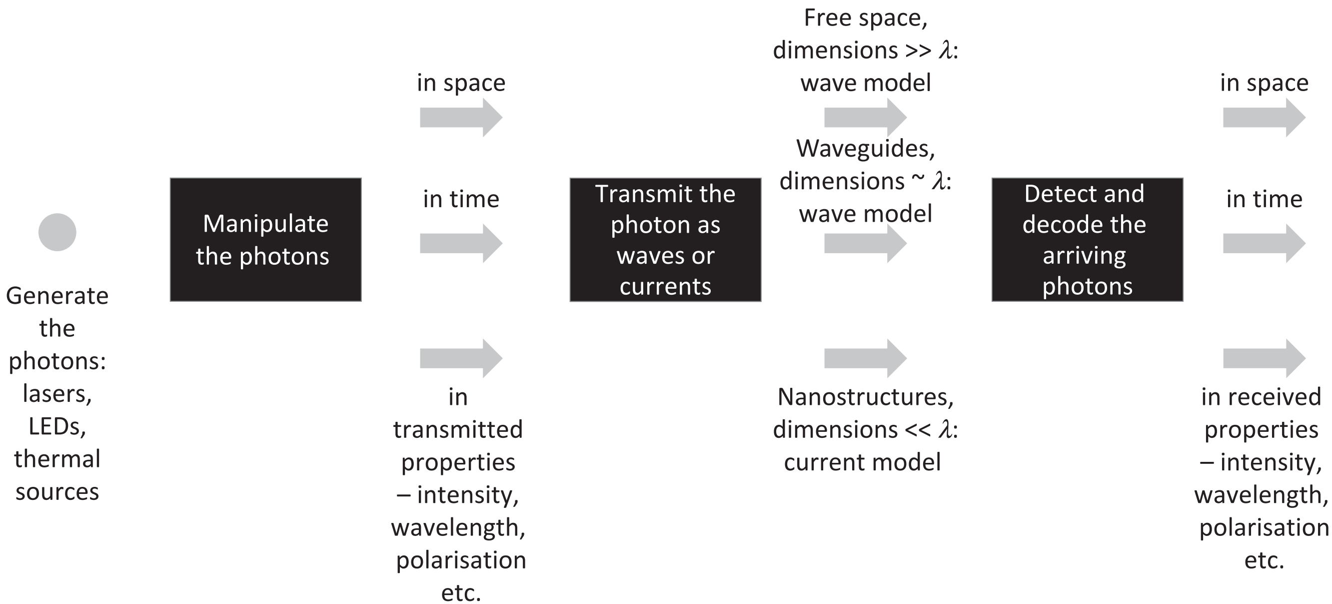

Figure 1.3 A picture of 'what is photonics': the generation, manipulation, transmission and detection of electromagnetic radiation in that region of the spectrum where the photon picture dominates the behaviour at generation and detection, but where transmission can be described in terms of waves, in large-scale dielectrics or in medium-scale waveguides. At the smallest scale, over very short distances, currents in conductors or in nano-scale synthetic dielectric structures, become important.

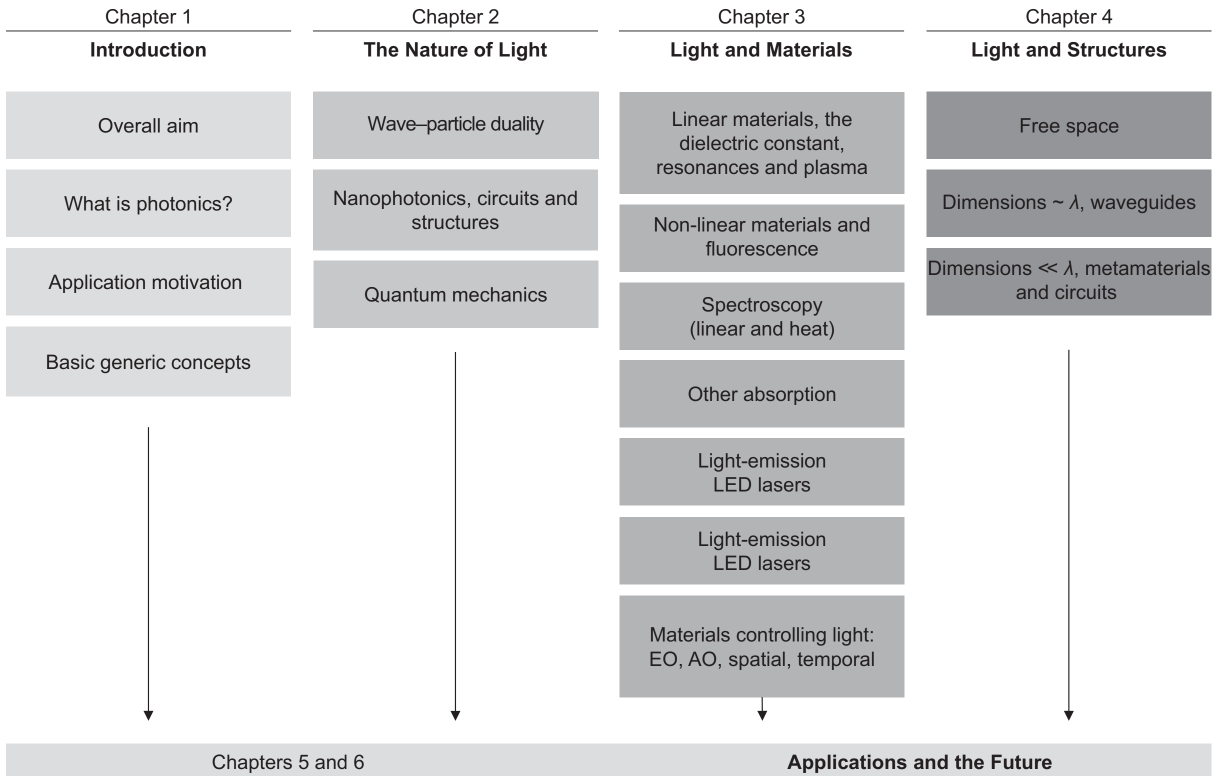

Figure 1.4 The essential concepts of photonics and their organisation in this book.

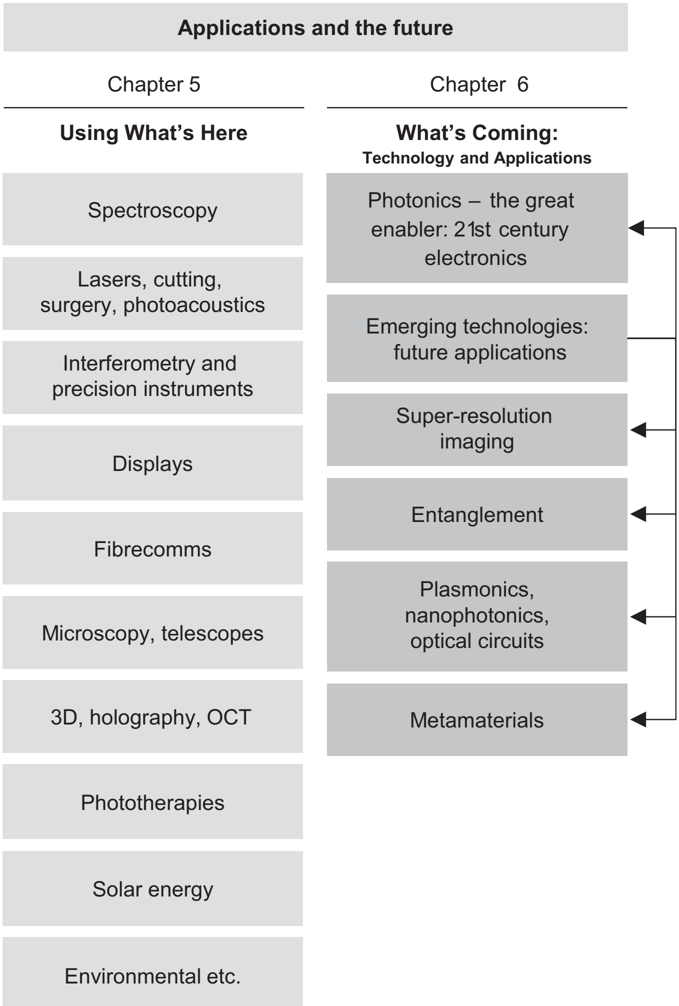

Figure 1.5 The present and future role of photonics in our developing society.

through further exploitation of what we already know or through the use of the new tools, as encapsulated in Figure 1.5.

1.5 Some Related Background Ideas

The best way of describing the interaction between light and a material depends on the nature and structure of the material and its dimensions. Resonance plays a large part in photonics; this occurs when the structural dimensions match the wavelength. The same phenomenon is familiar in musical instruments; long organ pipes resonate at lower frequencies than short ones. Resonant structures have entirely different propagation properties from an unstructured equivalent space and this applies in every day optics too, from the coatings on camera lenses to the colours of butterfly wings. The phenomenon whereby the dimension of a structure, in relation to the wavelength of an incident wave, affects the material properties seen by the wave is ubiquitous and powerful; it applies to every form of wave from mechanical resonances and acoustic waves to visible light and into the X-ray region. The same concept also explains much of quantum mechanics, particularly the ideas of energy levels and band structure. The concept of the 'universal wave' will be used extensively in what follows and, for a deeper and more thorough examination of this very powerful intuitive tool, there is little if anything to match J. R. Pierce's book (Further Reading A). Other conceptual tools are also extremely useful for an understanding of photonics; of these perhaps the *Fourier transform* is the most important. There is an extensive literature available, including a classic text by R. Bracewell and one by J. F. James (both listed in Further Reading A). Much of what is discussed here is also underpinned by Maxwell's equations, which themselves describe many of the interactions between electromagnetic waves and materials. Daniel Fleisch has produced a straightforward guide to these important relationships (see Further Reading A). At the other extreme, whilst the present text aims to introduce the basic concepts of photonics, the book by Saleh and Teich (see Further Reading C) presents over 1000 pages of comprehensive detail for those who may wish to go further.

Finally, the International Year of Light produced some inspiring texts (see Further Reading B) highlighting the critical contributions which light makes to our world and exploring the many photonic tools we can use to aid this exploration ranging from a mirror through a smart phone to the Hubble telescope.

1.6 Problems

Some topics to investigate:

1. How might the boundary lines for photonics, as indicated in Figure 1.2, change in deep space? Could there be circumstances where, for example, the photon concept is useful for describing an electromagnetic wave of 3 cm wavelength?

2. The term 'microwave photonics' appears fairly often in current scientific literature. What is likely to be the prime condition for the observation of microwave photons? Figures 1.1 and 1.2 might give some hints on this. Note that microwave photonics can also apply to the situation where a light beam is modulated by a microwave frequency signal.
3. Now think about a microwave communications satellite, in synchronous orbit about 22,400 miles above the earth where the ambient temperature is a few kelvins. Would you consider a communications satellite a photonic device and why? Some points to consider are that it is subject to the sun's rays for half the day, the internal circuits generate heat and the heat loss in what is essentially a vacuum will be primarily by radiation. *(It may be helpful to look up the satellite communications frequency band using a search engine. A great deal of useful background on many, many topics can be found in this way!)*
4. At the other end of the spectrum – when might X-rays with photon energies in the 100 V to 100 kV range behave as waves rather than particles?