17.1 Introduction and synopsis

It was at one time thought that the fact that light could travel through space — from the sun to the earth, for instance — must mean that space was not really empty but filled with 'luminiferous ether'. It was not until the experiments of Michelson[1] and Morley in 1857 that it was realised that light did not need a 'material' for its propagation but could propagate through totally empty space at what is now seen as the ultimate velocity: 3×10^8 m/s.

Light is electromagnetic (e-m) radiation — coupled waves of an electric and magnetic field. Materials interact with radiation by reflecting it, absorbing it, transmitting it, and refracting it. This chapter is about these interactions, the materials that do them best, and the ways we use them. The chapter opening page shows two: a reflecting telescope and a refracting microscope, each of which depend on the optical properties of materials.

17.2 The interaction of materials and radiation

Electromagnetic radiation permeates the entire universe. Observe the sky with your eye and you see the visible spectrum, the range of wavelengths we call 'light' (0.40—0.77 μm). Observe it with a detector of X-rays or γ-rays and you see radiation with far shorter wavelengths (as short as 10^{-4} nm, one thousandth the size of an atom). Observe it instead with a radio telescope and you pick up radiation with wavelengths measured in millimetres, metres, or even kilometres, known as radio and microwaves. The range of wavelengths of radiation is vast, spanning 18 orders of magnitude (Figure 17.1). The visible spectrum is only a tiny part of it — but even that has entrancing variety, giving colours ranging from deep purple through blue, green, and yellow to deep red.

The intensity I of an e-m wave, proportional to the square of the amplitude of the coupled e-m fields, is a measure of the energy it carries. When radiation with intensity I_o strikes a material, a part I_R of it is reflected, a part I_A absorbed, and a part I_T may be transmitted. Conservation of energy requires that

$$\frac{I_R}{I_o} + \frac{I_A}{I_o} + \frac{I_T}{I_o} = 1 \qquad (17.1)$$

The first term is called the *reflectivity* of the material, the second the *absorptivity*, and the last the *transmittability* (all dimensionless). Each depends on the wavelength of the radiation, on the nature of the material, and on the state of its surfaces, as well as its thickness (for absorption and transmission). They can be thought of as properties of the material in a given state of surface smoothness or roughness.

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[1] Albert A. Michelson (1852—1937), Prussian-American experimental physicist, who, with E. W. Morley, first demonstrated that the speed of light is independent of the earth's motion, a finding central to the establishment of the theory of relativity.

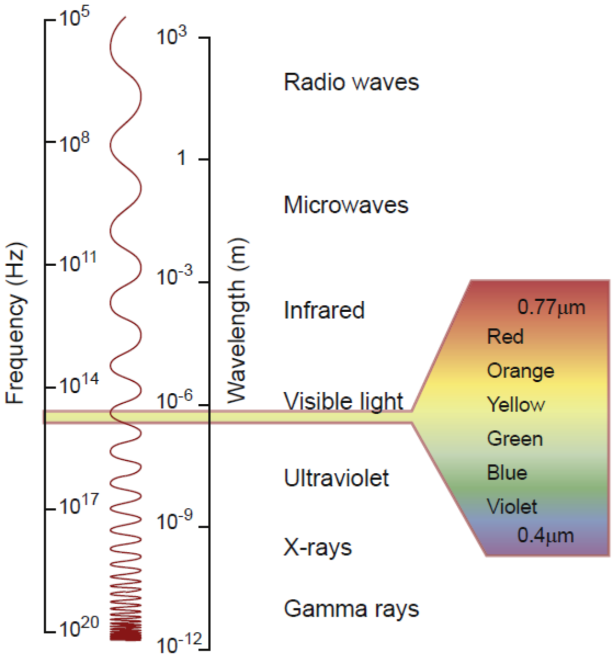

Figure 17.1 The spectrum of electromagnetic waves. The visible spectrum lies between the wavelengths 0.4 and 0.77 microns.

In optics we are concerned with wavelengths in the visible spectrum. Materials that reflect or absorb all visible light, transmitting none, are called *opaque* even though they may transmit in the near visible (infrared or ultraviolet). Those that transmit a little diffuse light are called *translucent*. Those that transmit light sufficiently well that you can see through them are called *transparent*; and a subset of these that transmit almost perfectly, making them suitable for lenses, light-guides, and optical fibres, are given the additional title of *optical quality*. To be transparent a material must be a dielectric. Metals, by contrast, are opaque; they reflect most of the light that strikes them.

Specular and diffuse reflection *Specular* surfaces are microscopically smooth and flat, meaning that any irregularities are much smaller than the wavelength of light. A beam of light striking a specular surface at an incident angle θ_1 suffers specular reflection, which means that it is reflected as a beam at an angle θ_2 (Figure 17.2(a)) such that

$$\theta_1 = \theta_2 \tag{17.2}$$

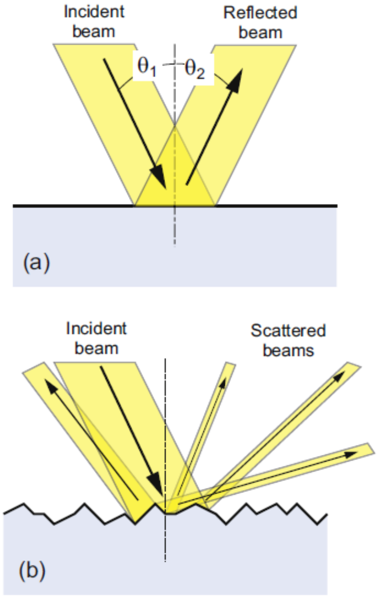

Figure 17.2 (a) Flat, reflective surfaces give specular reflection. (b) Rough surface gives diffuse reflection.

Diffuse surfaces are irregular; the law of reflection (equation (17.2)) still holds locally but the incident beam is reflected in many different directions because of the irregularities, as in Figure 17.2(b).

Absorption If radiation penetrates a material, some is absorbed. The greater the sample thickness through which the radiation passes, the greater the absorption. The intensity I, starting with the initial value I_o, decreases with distance x such that

$$I = I_o \exp - \beta x \tag{17.3}$$

where β is the absorption coefficient, with dimensions of m^{-1} (or, more conveniently, mm^{-1}). The absorption coefficient depends on wavelength, with the result that white light passing through a material may emerge with a colour corresponding to the wavelength that is least absorbed – that is why a thick slab of ice looks blue.

Transmission By the time a beam of light has passed completely through a slab of material, it has lost some intensity through reflection at the surface at which it entered, some in reflection at the surface at which it leaves, and some by absorption in between. Its intensity when it emerges at the other side is

$$I = I_o\left(1 - \frac{I_R}{I_o}\right)^2 \exp - \beta x \tag{17.4}$$

The term $(1 - I_R/I_o)$ occurs to the second power because intensity is lost through reflection at both surfaces.

Refraction The velocity of light in vacuum, $c_o = 3 \times 10^8$ m/s, is as fast as it ever goes. When it (or any other e-m radiation) enters a material, it slows down. The *index of refraction*, n, is the ratio of its velocity in vacuum, c_o, to that in the material, c:

$$n = \frac{c_o}{c} \tag{17.5}$$

This retardation makes a beam of light bend or *refract* when it enters a material of different refractive index. When a beam with an angle of incidence θ_1 passes from a material 1 of refractive index n_1 into a material 2 of index n_2, it deflects to an angle θ_2, such that

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_2}{n_1} \tag{17.6}$$

as in Figure 17.3(a); the equation is known as Snell's law[2]. The refractive index depends on frequency, so each of the colours that make up white light is refracted through a slightly different angle, producing a spectrum when light passes through a prism. When material 1 is vacuum or air, for which $n_1 = 1$, the equation reduces to

$$\frac{\sin\theta_1}{\sin\theta_2} = n_2 \tag{17.7}$$

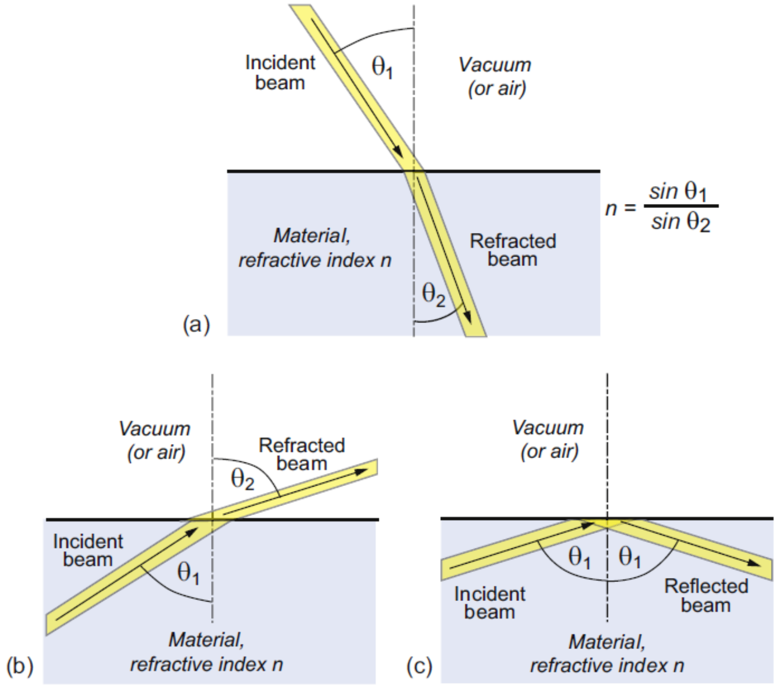

Figure 17.3 Refraction (a,b) and total internal reflection (c).

Equation (17.6) says that when light passes from a material with index $n_1 = n$ into air with $n_2 = 1$, it is bent away from the normal to the surface, like that in Figure 17.3(b). If the incident angle, here θ_1, is slowly increased, the emerging beam turns until it becomes parallel with the surface when $\theta_2 = 90°$ and $\sin\theta_2 = 1$. This occurs at an incident angle, from equation (17.6), of

$$\sin\theta_1 = \frac{1}{n} \tag{17.8}$$

For values of θ_1 greater than this, the equation predicts values of $\sin\theta_2$ that are greater than 1, and that can't be. Something strange has to happen, and it does: the ray is totally reflected back into the material as in Figure 17.3(c). This *total internal reflection* has many uses, one being to bend the path of light in prismatic binoculars and reflex cameras. Another is to trap light within an optical fibre, an application that has changed the way we communicate.

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[2] Willebrord Snell (1591–1626), Dutch astronomer, also known as Snell van Royen, or Snellius, who first derived the relationship between the different angles of light as it passes from one transparent medium to another. The lunar crater Snellius is named after him.

Reflection is related to refraction. When light travelling in a material of refractive index n_1 is incident normal to the surface of a second material with a refractive index n_2, the reflectivity is

$$R = \frac{I_R}{I_o} = \left(\frac{n_2 - n_1}{n_2 + n_1}\right)^2 \tag{17.9a}$$

If the incident beam is in air, with a refractive index very close to 1, this becomes

$$R = \frac{I_R}{I_o} = \left(\frac{n - 1}{n + 1}\right)^2 \tag{17.9b}$$

Thus materials with a high refractive index have high reflectivity. When a transparent material with a high reflectivity is coated with a second transparent material with a lower reflectivity, rays are reflected from both the front and the back surfaces of the coating. The quadratic nature of equations (17.9a,b) causes the overall reflectivity – the sum of the intensities from the front surface and from the back – to decrease. If the refractive index of the starting material is n_2, that of the coating is n_1, and that of the surrounding medium (usually air) is n_o, then the optimum value for the index n_1 of the coating is

$$n_1^{\text{opt}} = \sqrt{n_o n_2} \tag{17.10}$$

Thus the optimum refractive index for a coating to minimise reflectivity (and thereby maximise transmission) for a flint glass window with a refractive index of 1.61 is $n_1^{\text{opt}} = \sqrt{1.161} = 1.27$.

Before leaving Snell and his law, ponder for a moment the odd fact that the beam is bent at all. Light entering a dielectric, as we have said, slows down. If that is so, why does it not continue in a straight line, just more slowly? Why should it bend? To understand this we need Fresnel's[3] construction. We think of light as advancing via a series of wave-fronts. Every point on a wave-front acts as a source, so that, in a time Δt, the front advances by $v\Delta t$, where v is the velocity of light in the medium through which it is passing ($v = c$ in vacuum or air) – as shown in Figure 17.4 with *Wave-front 1* advancing $c\Delta t$. When the wave enters a medium of higher refractive index it slows down so that the advance of the wave-front within the medium is less than that outside, as shown with *Wave-front 2* advancing $v\Delta t$ in the figure. If the angle of incidence θ_1 is not zero, the wave-front enters the second medium progressively, causing it to bend, so that when it is fully in the material it is travelling in a new direction, characterised by the angle of refraction, θ_2. Simple geometry then gives equation (17.6).

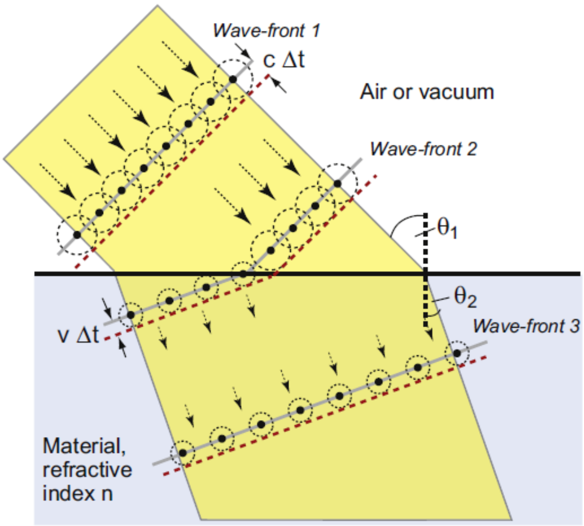

Figure 17.4 The Fresnel construction.

Interference The rainbow sheen of a compact disc when viewed obliquely, the iridescence of soap bubbles and oil films, even the colours of peacock feathers and butterfly wings, are caused by interference.

When a transparent layer coats a surface, the impinging light is both reflected from it and transmitted through. If the transmitted portion is reflected at the back surface of the film it returns to the front surface and interferes with the incoming light (Figure 17.5). The nature of

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[3] Augustin Jean Fresnel (1788–1827), French physicist and engineer, known for his research on the wave theory of light and of diffraction and polarisation.

the interference depends on the difference in the *optical path length* between the incoming and the reflected light. Optical path length L_{opt} is defined by

$$L_{\text{opt}} = \sum_i n_i d_i \tag{17.11}$$

where n_i is the refractive index of the ith material along the path, and d_i is the physical length of the segment of the path. The difference in optical path length between two rays determines whether the interference is constructive or destructive. If this difference is ΔL_{opt}, the phase difference between the two rays is

$$\Delta\varphi = \frac{2\pi\,\Delta L_{\text{opt}}}{\lambda}$$

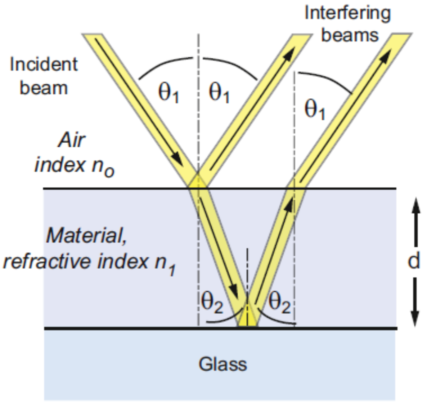

Figure 17.5 Waves reflected from the front and back surface of thin films interfere.

The two waves are in phase with

$$\frac{\Delta L_{\text{opt}}}{\lambda} = 0, \pm 1, \pm 2, \ldots \tag{17.12a}$$

and they are half a cycle out of phase when

$$\frac{\Delta L_{\text{opt}}}{\lambda} = \pm\frac{1}{2}, \pm\frac{3}{2}, \pm\frac{5}{2}, \ldots \tag{17.12b}$$

Interference is constructive when the waves are in phase, destructive interference when they are half a cycle out of phase (Figure 17.6). If the two interfering rays have the same amplitude, constructive interference doubles it, destructive interference kills it completely. All this only works if the differences in optical path length are small. If they are more than a few wavelengths the phase relationship between the rays is lost.

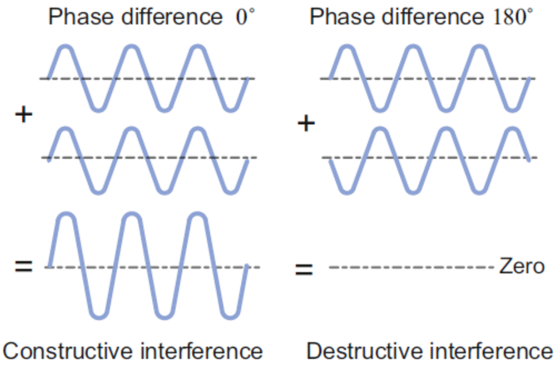

Figure 17.6 Constructive and destructive interference.

17.3 Charts for optical properties

Refractive index and dielectric constant Figure 17.7 shows the refractive index, n, of dielectrics, plotted against the dielectric constant ε_R (defined in Chapter 15). Those shown as white bubbles are transparent to visible light; those with red bubbles are not but transmit radiation of longer wavelengths (germanium, for instance, is used for lenses for infrared imaging). Note the wide and continuous range of the refractive index of glasses, determined by their chemistry. This ability to control n by manipulating composition is central to the selection of materials for lenses and optical fibres. The relationship between n and ε_R is explored in Section 17.4.

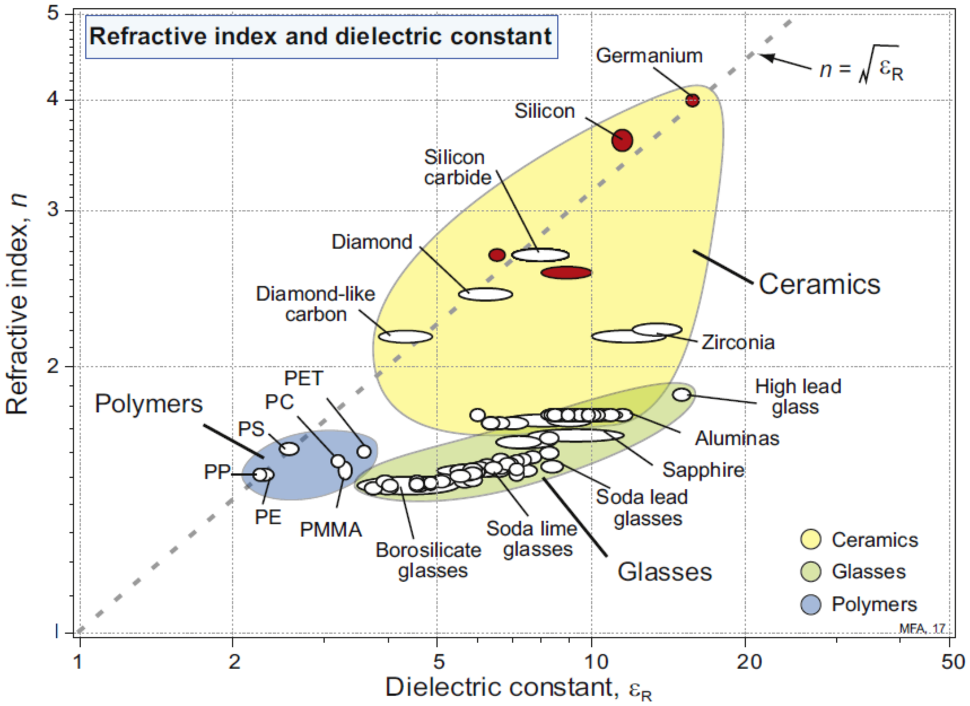

Figure 17.7 A chart of refractive index and dielectric constant, showing the approximate relationship $n = \sqrt{\varepsilon_R}$.

17.4 Drilling down: the physics and manipulation of optical properties

Light, like all radiation, is an e-m wave. The coupled fields are sketched in Figure 17.8. The electric part fluctuates with a frequency ν that determines where it lies in the spectrum of Figure 17.1. The fluctuating electric field and magnetic field are in phase with one another. A plane-polarized beam looks like this one: the electric and magnetic fields lie in fixed planes. Natural light is not polarised; the wave also rotates so that the plane containing each wave continuously changes.

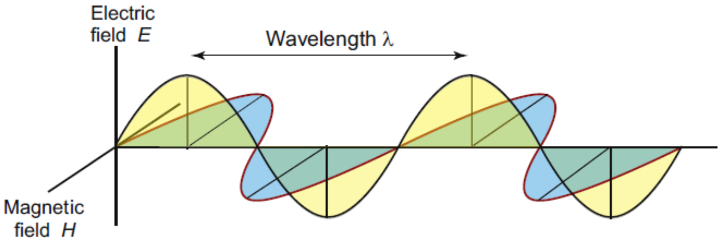

Figure 17.8 An electromagnetic wave. The electric component (yellow) is in phase with the magnetic component (blue).

Light slows down when it enters a dielectric because the electric field polarises the ions or molecules in the way that was illustrated in Figure 15.17. The field displaces charge to create electric dipoles, the strength of which depends on the charge and the displacement, so larger ions tend to have a larger dipole moment, giving a larger dielectric constant and a larger refractive index. Ordinary soda-lime glass (roughly 70% SiO_2, 20% Na_2O, and 10% CaO) has a refractive index of 1.52. If most of these oxides are replaced by the oxide of lead (PbO), the large Pb ion increases the polarisability and the refractive index increases to 2.0. Dielectrics with an amorphous or cubic structure are optically isotropic, meaning that their refractive index is independent of the direction that the light enters the material. Non-cubic crystals are anisotropic, meaning that their refractive index depends on direction, which is greatest in directions with the greatest ion density.

Many aspects of radiation are most easily understood by thinking of it as a wave. Others need a different picture – that of radiation as discrete packets of energy, or *photons*. The idea of a wave that is also like a particle with a discrete energy is not intuitive – it is another of the results of quantum theory that do not correspond to ordinary experience. The energy E_{ph} of a photon of radiation of frequency v or wavelength λ is

$$E_{ph} = hv = \frac{hc}{\lambda} \tag{17.13}$$

where h is Planck's[4] constant (6.626×10^{-34} J.s) and c is the speed of the radiation. Thus radiation of a given frequency has photons of fixed energy, regardless of its intensity – an intense beam simply has more of them. This is the key to understanding reflection, absorption, and transmission.

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[4] Max Karl Ernst Ludwig Planck (1858–1947), a central figure in the development of quantum theory; it was he who formulated equation (17.13).

Why aren't metals transparent? Recall from Chapter 4 that the electrons in materials circle their parent atom in orbits with discrete energy levels, and only two can occupy the same level. Metals have a large number of very closely spaced levels in their conduction band; the electrons in the metal only fill part of this number. Filling the levels in a metal is like pouring water into a container until it is part full: its surface is the Fermi level, and levels above it are empty. If you 'excite' the water – say by shaking the container – some of it can slosh to a higher level. If you stop shaking, it will return to its Fermi level.

Radiation excites electrons, and in metals there are plenty of empty levels in the conduction band into which they can be excited. But here quantum effects cut in. A photon with energy $h\nu$ can excite an electron only if there is an energy level that is exactly $h\nu$ above the Fermi level – and in metals there is. So all the photons of a light beam are captured by electrons of a metal, regardless of their wavelength. Figure 17.9 shows, on the left, what happens to just one.

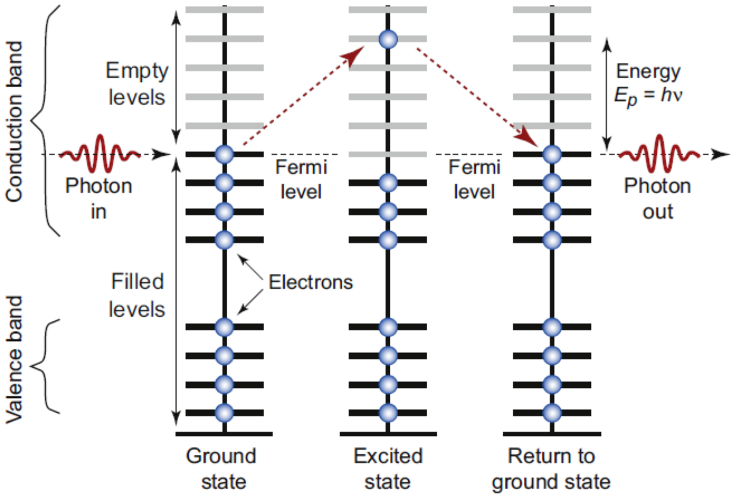

Figure 17.9 Metals absorb photons, capturing their energy by promoting an electron from the filled part of the conduction band into a higher, empty level. When the electron falls back, a photon is re-emitted.

What next? Shaken water settles back, and the electron does the same. In doing so it releases a photon with exactly the same energy that excited it in the first place, but in a random direction. Any photons moving into the material are immediately recaptured, so none make it more than about 0.01 μm (about 30 atom diameters) below the surface. All, ultimately, re-emerge from the metal surface – that is, they are reflected. Many metals (silver, aluminium, and stainless steel, for example) reflect all wavelengths almost equally well, so if exposed to white light they appear silver. Others (copper, brass, and bronze) reflect some colours better than others and appear coloured because, in penetrating this tiny distance into the surface, some wavelengths are slightly absorbed.

Reflection by metals, then, has to do with electrons at the top of the conduction band. These same electrons provide electrical conduction. For this reason, the best metallic reflectors are the metals with the highest electrical conductivities – the reason that high-quality mirrors use silver and cheaper ones use aluminium.

How does light get through dielectrics? If electrons snatch up photons, how is it that some materials are transparent – light goes straight through them? Non-metals interact with radiation in a different way. Part may be reflected but much enters the material, inducing both dielectric and magnetic responses. Not surprisingly, then, the velocity of an e-m wave depends on the dielectric and magnetic properties of the material through which it travels. In vacuum the velocity is

$$c_o = \frac{1}{\sqrt{\varepsilon_o \mu_o}} \tag{17.14}$$

where ε_o is the electric permittivity of vacuum and μ_o its magnetic permeability, as defined in Chapters 15 and 16. Within a material its velocity is

$$c = \frac{1}{\sqrt{\varepsilon \mu}} \tag{17.15}$$

where $\varepsilon = \varepsilon_R \varepsilon_o$ and $\mu = \mu_R \mu_o$ are the permittivity and permeability of the material. The refractive index therefore is

$$n = \frac{c_o}{c} = \sqrt{\varepsilon_R \mu_R} \tag{17.16}$$

The relative permeability μ_R of most dielectrics is very close to unity – only the magnetic materials of Chapter 16 have larger values. Thus

$$n = \sqrt{\varepsilon_R} \tag{17.17}$$

The chart of Figure 17.7 has n as one axis and ε_R as the other. The diagonal line is a plot of this equation (the log scales make it a straight line). Polymers and very pure materials like diamond, silicon, and germanium lie close to the line but the agreement with the rest is not so good. This is because refractive index and dielectric constant depend on frequency. Refractive index is usually measured optically, and that means optical frequencies, around 10^{15} Hz. Dielectric constants are more usually measured at radio frequencies or below – 10^6 Hz or less. If the two are measured at the same frequency, equation (17.17) holds.

The reason that radiation can enter a dielectric is that its Fermi level lies at the top of the valence band, just below a band gap (Chapter 15 and Figure 17.10). The conduction band, with its vast number of empty levels, lies above it. To excite an electron across the gap requires a photon with an energy at least as great as the width of the gap, ΔE_{gap}. Thus radiation with photon energy less than ΔE_{gap} cannot excite electrons — there are no energy states within the gap for the electron to be excited into. The radiation sees the material as transparent, offering no interaction of any sort, so it goes straight through.

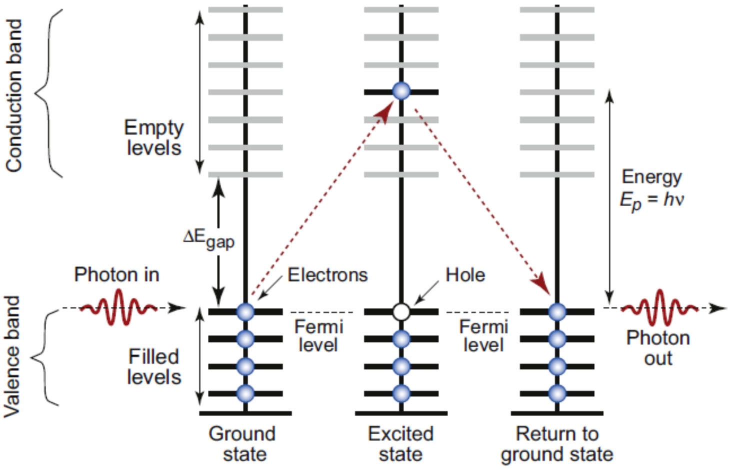

Figure 17.10 Dielectrics have a full band, separated from the empty conduction band by an energy gap. The material cannot capture photons with energy less than ΔE_{gap}, meaning that, for those frequencies, the material is transparent. Photons with energy greater than ΔE_{gap} are absorbed, as illustrated here.

Electrons are, however, excited by radiation with photons with energies greater than ΔE_{gap} (i.e. higher frequency, shorter wavelength). These have enough energy to pop electrons into the conduction band, leaving a 'hole' in the valence band from which they came. When they jump back, filling the hole, they emit radiation of the same wavelength that first excited them, and for these wavelengths the material is not transparent (Figure 17.10). The critical frequency ν_{crit}, above which interaction starts, is given by

$$h\nu_{crit} = \Delta E_{gap} \tag{17.18}$$

The material is opaque to frequencies higher than this. Thus bakelite is transparent to infrared light because its frequency is too low and its photons too feeble to kick electrons across the band gap. The visible spectrum has higher frequencies with more energetic photons, exceeding the band gap energy; they are captured and reflected.

Although dielectrics can't absorb radiation with photons of energy less than that of the band gap, they are not all transparent. Most are polycrystalline and have a refractive index that depends on direction; then light is *scattered* as it passes from one crystal to another. Imperfections, particularly porosity, do the same. Scattering, sketched in Figure 17.11, makes the material appear translucent or opaque, even though, when made as a perfect single crystal, it is completely transparent. Thus sapphire (alumina, Al_2O_3), used for watch crystals and cockpit windows of aircraft, is transparent, but the polycrystalline, slightly porous form of the same material that is used for electronic substrates is translucent or opaque. Scattering explains why some polymers are translucent or opaque: their microstructure is a mix of crystalline and amorphous regions with different refractive indices. It explains, too, why some go white when you bend them: it is because light is scattered from internal micro-cracks – the crazes described in Chapter 6.

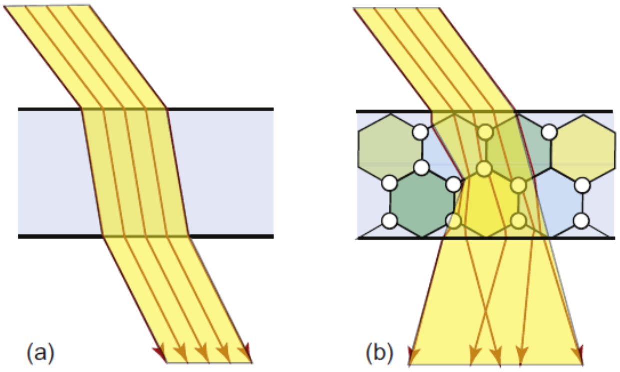

Figure 17.11 (a) A pure glass with no internal structure and a wide band gap is completely transparent. (b) Light entering a polycrystalline ceramic or a partly crystalline polymer suffers multiple refractions and is scattered by porosity, making it translucent.

Colour If a material has a band gap with an energy ΔE_{gap} that lies within the visible spectrum, the wavelengths with energy greater than this are absorbed and those with energy that is less are not. The absorbed radiation is re-emitted when the excited electron drops back into a lower energy state, but this may not be the one it started from, so the photon it emits has a different wavelength than the one that was originally absorbed. The light emitted from the material is a mix of the transmitted and the re-emitted wavelengths, giving it a characteristic colour.

More specific control of colour is possible by doping – the deliberate introduction of impurities that create a new energy level in the band gap, as in Figure 17.12. Radiation is absorbed as before but it is now re-emitted in two discrete steps as the electrons drop first into the dopant level, emitting a photon of frequency $\nu_1 = \Delta E_1/h$ and from there back into the valence band, emitting a second photon of energy $\nu_2 = \Delta E_2/h$. Particularly pure colours are created when glasses are doped with metal ions: copper gives blue; cobalt, violet; chromium, green; manganese, yellow.

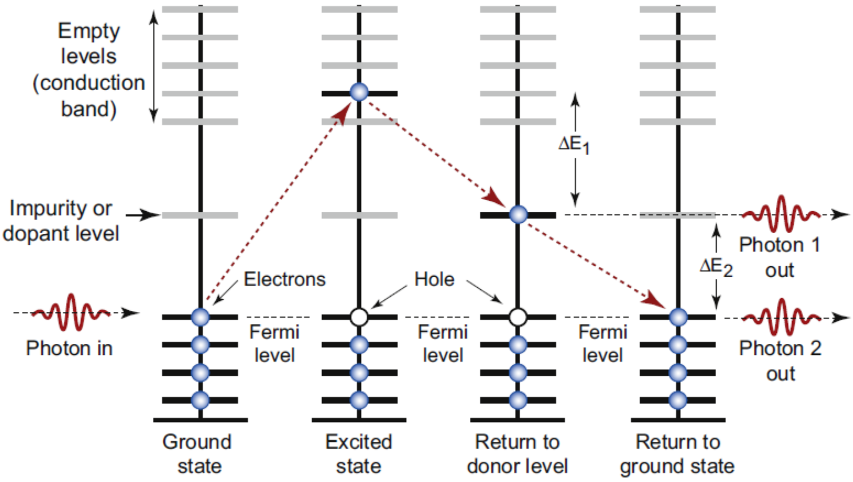

Figure 17.12 Impurities or dopants create energy levels in the band gap. Electron transitions to and from the dopant level emit photons of specific frequencies and colours.

Chromisity *Photochromic* materials change colour when subjected to sunlight. Photochromic glass contains nano-crystalline silver halide particles that ionise when exposed to UV light, absorbing visible light. *Thermochromic* materials change colour when their temperature changes because of a thermally-induced phase transformation. *Electrochromic* materials change colour in an electric field. Electrochromic glass dims to a darker colour while still remaining transparent. Electrochromic polymers switch from transparent to opaque. Electrochromic windows allow dynamic control of daylight and solar heat gain in buildings, vehicles, aircraft, and ships. *Dichroic* (literally, 'two-colour') surfaces exhibit colours that change with the angle of view. They are built up of thin layers with different light transmission, absorption, and reflection qualities. The colour comes from interference between rays reflected from different layers or from differential absorption of differing wavelengths within layers.

Fluorescence, phosphorescence, and chemo-luminescence Electrons can be excited into higher energy levels by incident photons, provided they have sufficient energy. Energetic electrons, like those of the electron beam of a cathode ray tube, do the same. In most materials the time delay before the electrons drop back into lower levels, re-emitting the energy they captured, is extremely short, but in some there is a delay. If, on dropping back, the photon they emit is in the visible spectrum, the effect is that of *luminescence* — the material continues to glow even when the incident beam is removed. When the time delay is fractions of seconds, it is called *fluorescence*, used in fluorescent lighting where it is excited by UV from a gas discharge, and in displays and LED lighting where it is excited by the UV of LEDs. When the time delay is longer it is called *phosphorescence*; it is no longer useful for creating moving images but is used instead for static displays like that of watch faces, where it is excited by electrons (β particles) released by a mildly radioactive ingredient in the paint. In *chemo-luminescence* the excitation derives instead from a chemical reaction, as in fireflies and the luminous fish and algae of the ocean.

Photoconductivity Dielectrics are true insulators only if there are no electrons in the conduction band, since if there are any, a field will accelerate them giving an electric current. Some dielectrics have a band gap that is sufficiently narrow that the photons of visible light excite electrons across it, and hence become conducting (though with high resistance) when exposed to light. The greater the intensity of light, the greater is the conductivity. Photo light meters use this effect; the meter is simply a bridge circuit measuring the resistance of a photo-conducting element such as cadmium sulphide.

17.5 Optical design

There are many methods for producing thin ceramic, glass, or polymer films or coatings with controlled optical properties. Many of these methods rely on processing by physical vapour deposition (PVD) or chemical vapour deposition (CVD).

Using reflection and refraction Telescopes, microscopes, cameras, and car headlights all rely on the focusing of light. Reflecting telescopes and car headlights use metallised glass or plastic surfaces, ground or moulded to a concave shape; the metal, commonly, is silver because of its high reflectivity across the entire optical spectrum.

Refracting telescopes, microscopes, and cameras use lenses. Here the important property is the refractive index and its dependence on wavelength (since if this is large, different wavelengths of light are brought to focus in different planes) and the reflectivity (since reflected light is lost and does not contribute to the image). As the chart of Figure 17.7 shows, most elements and compounds have a fixed refractive index. Glasses are different: their refractive index can be tuned to any value between 1.5 and more than 2. Adding components with light elements like sodium (as in soda-lime glass) gives a low refractive index; adding heavy elements like lead (as in lead glass or 'crystal') gives a high one.

Using total internal reflection Optical fibres have revolutionised the digital transmission of information: almost all landlines now use these rather than copper wires as the 'conductor'. A single fibre consists of a core of pure glass contained in a cladding of another glass with a larger refractive index, as in Figure 17.13. A digitised signal is converted into optical pulses by an LED. The stream of pulses is fed into the fibre where it is contained within the core, even when the fibre is bent, because any ray striking the core-cladding interface at a high angle of incidence suffers total internal reflection. The purity of the core – a silica glass – is so high that absorption is very small; occasional repeater stations are needed to receive, amplify, and retransmit the signal to cover long distances.

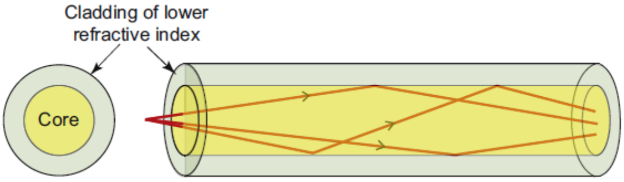

Figure 17.13 An optical fibre. The graded refractive index traps light by total internal reflection, making it follow the fibre even when it is curved.

Using interference The total amount of light impinging on a surface must in sum be reflected, transmitted, or absorbed (equation (17.1)). If the reflection is reduced, more must be transmitted. Anti-reflective coatings, common on computer screens, eyeglasses, and camera lenses, are designed to reduce reflection (cutting down glare), to increase light transmission through a surface, and to increase contrast. They consist of single or multiple layers of transparent thin films with different refractive indices, chosen to produce destructive interferences for reflected light and constructive interferences for light that is transmitted. The effectiveness varies with the wavelength of the light and its incident angle. In current practice, anti-reflective coatings are designed for optimal performance for specified wavelengths and angles, commonly for infrared, visible, and ultraviolet spectra, depending on the application.

Fundamental effects of layering are shown in Figures 17.5 and 17.14. Consider a design intended to optimise light transmission in a system consisting of a simple one-layer coating on glass. The light reflects twice, once from the surface to the air and once from that between the layer and the glass. The reflectivity of a material depends on its refractive index in the way described by equation (17.9). If R_f and R_g are the reflectivities at the surface-to-air and surface-to-glass interfaces, the transmission at each interface is $T_f = (1 - R_f)$ and $T_g = (1 - R_g)$ and, neglecting absorption, the total transmission is $T_f T_g$.

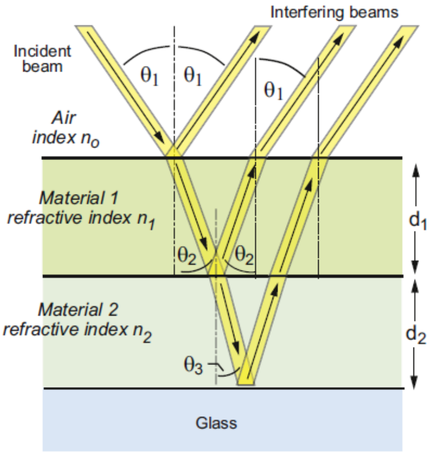

Figure 17.14 Multi-layers allow fine tuning of the reflectance and transmittance of glass.

Suppose now that the layer is very thin, and a plane wave falls on its surface. If the angle of incidence is 0°, meaning that the wave is normal to the layer surface, then waves reflected from the back surface travel along a longer optical path than those reflected from the front. The optical path difference for a wave reflected at the air surface and one reflected from the back of the layer, for normal illumination, is

$$\Delta L_{\text{opt}} = 2n_1 d$$

When, instead, the incident wave is not normal to the surface, the optical path difference can be longer, as illustrated in the figure. Destructive interference occurs when this is equal to $\frac{1}{2}\lambda$, $\frac{3}{2}\lambda$, etc. Thus a single layer can be tuned for destructive interference, cancelling reflection, for a single wavelength, and for angle of viewing, though wavelengths and angles near these will show partial cancellation. Cancellation for a wider range of wavelengths and viewing angles is possible with multi-layers like that shown in Figure 17.14, often achieved with alternating layers of silica (SiO_2, which has a low refractive index) and titanium dioxide (TiO_2, which has an exceptionally large one).

17.6 Summary and conclusions

Materials interact with electromagnetic radiation in several ways: reflecting it, refracting it, and absorbing it. This is because radiation behaves both as a wave of frequency ν and as a stream of discrete photons with energy $E_{\text{ph}} = h\nu$. Electrons in materials capture photons, grabbing their energy, provided there are energy levels exactly E_{ph} above their ground state for them to occupy. After a time delay that is usually very short, the electrons drop back down to their ground state, re-emitting their energy as new photons. In metals there are always usable energy levels so every photon hitting a metal is captured and thrown back out, giving reflection. In a dielectric, the atoms ignore low-frequency, low-energy photons, and capture only those with energy above a critical level set by the band gap. Those that are not caught pass straight through; for these frequencies, the material is transparent. Doping introduces extra slots within the band gap for electrons to fall into as they release their energy, and in doing so they emit photons of specific frequency and colour.

When radiation enters a dielectric, it slows down. A consequence of this is that a beam entering at an angle is bent — the phenomenon of refraction. It is this that allows light to be focussed by lenses, reflected by prisms, and trapped in fine, transparent fibres to transmit information.

Of all the transparent materials at our disposal, glasses offer the greatest range of refractive index and colour. Glasses are based on amorphous silica (SiO_2). Silica is an extremely good solvent, allowing a wide range of other oxides to be dissolved in it over a wide range of concentrations. It is this that allows the optical properties of glasses to be adjusted and fine-tuned to match design needs.