1 Introduction

Science experiments are performed to gain information about a sample. There are many different ways to interrogate a sample. Nature is exacting though, and will only answer the specific question that is asked. The different techniques discussed in this book are all asking slightly different questions, usually with light. It is important to keep in mind exactly what question you are asking with each experimental technique in order to correctly interpret the data.

Light carries information. This is a critical point to keep in mind. For instance, light reflecting off of objects brings information to your eyes and brain about your surroundings. Light from the sun provides astronomers information about our nearest star's composition and temperature. And light transmitted through undersea cables enables sharing cat videos and stock market fluctuations with your friends and colleagues on other continents.

Experimental optics is all about using light to bring you the information you need about your sample and the physical world. Naturally, light can carry many different types of information. As you use optics to ask physical questions of your samples, it is essential that you can control the light you are using and choose the correct form of it so that you can extract the right type of information.

This book aims to help you do exactly that. We cover the basic principles of light and optics in Chapter 1, and then the different optical components used to manipulate light in Chapter 2. Chapter 3 is about spectroscopic techniques, which provide a wealth of information about the sample. Chapter 4 is about the plethora of optical microscopy techniques. Finally, Chapter 5 covers some of the practical tips and tricks for setting up your own optical experiments.

If you take nothing else from this book, remember that:

- light carries information;
- to get the information you want, you need to choose the correct form of light.

1.1 Light: A Brief Introduction to its Properties

This section is a quick introduction to some important concepts about light that will be used in the rest of the book. It is by no means an exhaustive course in optics.

1.1.2 What is Light?

Light is electromagnetic radiation. It can be modeled in two ways: as a wave or as a particle (a "photon"). Scientists switch back and forth between the two models of light depending on the physical phenomenon that they are describing (Appendix 2).

The wave-like nature of light was demonstrated by Thomas Young's double slit experiment in 1801 in which he observed constructive and destructive interference between two light beams (Appendix 3). The particle nature of light was used by Albert Einstein to explain the photoelectric effect (Appendix 1), for which he was awarded the Nobel Prize in 1921. In the photoelectric effect, light incident on a metal ejects electrons. The more intense the light, the more electrons are ejected, but all the electrons have the same energy. This means that each photon of the same color has the exact same amount of energy. If light acted only as a wave, illuminating the sample with light of higher intensity should produce ejected electrons with higher energies.

Which model of light is correct? Both and neither are correct. By using the appropriate model, different optical phenomena can be quite accurately described, but clearly a perfect model would describe all optical phenomena without the need to jump back and forth between two different models. The mathematically unified description of electromagnetic radiation is beyond the scope of this book, so for now please accept the need to jump back and forth between conceptual models.

In the wave model, light consists of oscillating electric and magnetic fields that are both orthogonal (i.e., perpendicular) to each other and orthogonal to the propagation direction of the light (Figure 1.1). The electric field of light is the component that predominantly interacts with matter (e.g., your sample), so to describe light–matter interactions you can usually ignore the magnetic field. The intensity of the light is the magnitude of the electric field squared.

Light waves can be described by their wavelength or their frequency. Wavelength is the distance from one peak in the wave to the next peak in the wave. Wavelength is a distance and is measured in meters. Visible light is usually described in terms of wavelength. Visible light for humans ranges from 400 to 800

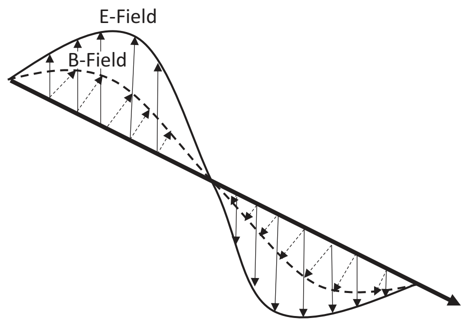


Figure 1.1

Light is electromagnetic radiation that consists of perpendicular electric and magnetic fields that are orthogonal to the direction of the propagation of light. The electric field is traditionally denoted with E and the magnetic field is traditionally denoted with B. The magnetic field is largely ignored in optics and only the interaction of the electric field with matter is considered.

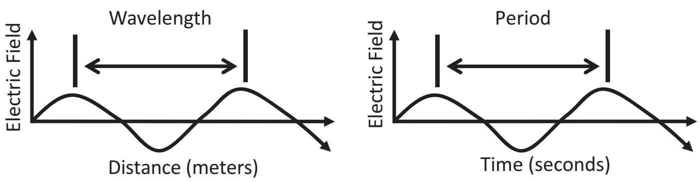


Figure 1.2

Waves can be described in terms of either wavelength or frequency, which equals 1/period.

nanometers (nm) in wavelength. One nanometer is 10^{-9} meters. Frequency is the reciprocal of the period (the time for the electric field to go from one peak to the next). Frequency is measured in hertz (Hz), which describes the number of peaks, or cycles, per second. Radio waves, also an electromagnetic wave, are usually described by their frequency. The local radio station is 90.9 MHz, for example.

In the particle model, light can be described by the energy of a single photon. The energy of a photon is usually described in units of electron volts (eV). Photons have no mass, so they can be easily created and destroyed without violating the law of conservation of mass. Photons do obey the law of conservation of energy. Also, despite having no mass, photons do have momentum, so they do obey conservation of momentum too. This property can be taken advantage of for solar sails for interplanetary probes and for optical tweezers and optical traps in a microscope.

In the particle model of light, each photon contains a discrete, well-defined, amount of energy. The energy of a photon is directly related to the frequency in the wave model and thus wavelength by the de Broglie relation:

$$E = h\nu = \frac{hc}{\lambda} \quad (1.1)$$

where E is the energy of a single photon;

h is Planck's constant (6.626×10^{-34} Js, where J stands for Joules, a unit of energy, and s stands for seconds);
ν is the frequency of light; and
λ is the wavelength of light.

TIP: The shorthand "hν" is often used instead of the word "photon" in pictures and diagrams.

There is a direct relation between the wavelength and the frequency of light:

$$c = \lambda\nu \quad (1.2)$$

where c is the speed of light in a vacuum (3×10^8 m/s);

λ ("lamb-dah") is the wavelength of light; and
ν ("new") is the frequency of light.

From Equation (1.2), a 400 nm photon (a purple photon) contains twice the energy of an 800 nm photon (a red photon). The perceived color of light is thus directly related to the energy of the photon or the wavelength and frequency of the light wave. Scientists often refer to things as "red shifted" when the light shifts down in energy and "blue shifted" when light shifts up in energy.

The electromagnetic spectrum is traditionally split into different ranges. The visible light range (400–800 nm, spanning violet to red) is the one that we are most familiar with. Just outside the visible light range are ultraviolet (UV) light (100–400 nm) range and infrared (IR) light (800–50,000 nm) range. The IR region is commonly split into the near IR (800–3,000 nm), mid-IR (3–25 μm), and far-IR regions (25–50 μm). Light below 190 nm is referred to as vacuum UV (VUV) because it is strongly absorbed by molecules in the air, and can only propagate through a vacuum. Light in the 1–100 nm wavelengths are referred to as extreme UV (EUV). Light with a wavelength shorter than the UV range is commonly referred to as soft x-rays, then hard x-rays, then gamma rays. Light with wavelengths longer than that in the IR region is referred to as microwaves and then radio waves. The exact cutoffs for the different regions vary depending on who you are talking to, but the values given in Table 1.1 are good general guides.

Table 1.1 Different regimes of the electromagnetic spectrum.

	Wavelength	Energy	Frequency	Example
Gamma rays	<0.01 nm	>124 keV	$>3 \times 10^{13}$ MHz	Radioactive decay
Hard x-rays	0.1–0.01 nm	12.4–124 keV	3×10^{12}–3×10^{13} MHz	Synchrotron
Soft x-rays	0.1–10 nm	124 eV–12.4 keV	3×10^{10}–3×10^{12} MHz	
Extreme ultraviolet (EUV)	1–100 nm	12.4 eV–1.24 keV	3×10^{9}–3×10^{11} MHz	Lithography (Section 4.20)
Vacuum ultraviolet (VUV)	100–190 nm	6.53–12.4 eV	3×10^{9}–1.5×10^{9} MHz	
Ultraviolet light (UV)	190–400 nm	3.1–6.53 eV	1.5×10^{9} MHz–7.5×10^{8} MHz	Sun burn
Visible light (VIS)	400–800 nm	1.55–3.1 eV	7.5×10^{8}–3.7×108 MHz	What you see
Near infrared (NIR)	800–3000 nm	0.413–1.55 eV	3.7×10^{8}–1.0×108 MHz	Night vision goggles
Mid-infrared (MIR)	3–25 μm	50–413 meV	1.0×10^{8}–1.2×10^{7} MHz	Heat/thermal imaging
Far-infrared (FIR)	25–50 μm	25–50 meV	1.2×10^{7}–5.88×10^{6} MHz	Rarely used
Terahertz (THz)	10 μm–1 mm	124–1.24 meV	0.3–30 THz	Medical imaging, security
Microwaves	1 mm–1 m	1.24 meV–1.24 μeV	300 MHz–300 GHz	Wi-Fi, cell phone communications
Radio waves	>1 m	<1.24 μeV	<300 MHz	AM/FM radio

1.2 An Explanation of Energy, Wavelength, and Frequency Jargon

Note that various frequency, wavelength, and energy units are preferred for different wavelength regimes, since using so many powers of 10 with a single unit is quite impractical. Table 1.2 shows the preferred units for each regime of the electromagnetic spectrum. Note that the unit cm^{-1} is known as the “wavenumber” and is a unit of energy corresponding to 0.00012 eV that is typically used to describe the MIR and FIR infrared regimes. For instance, one might say, “a peak

Table 1.2 The most commonly used units for various regions of the electromagnetic spectrum

	Wavelength	Energy	Frequency
Gamma rays	–	keV, MeV, GeV	–
Hard x-rays	Å, nm	keV	–
Soft x-rays	Å, nm	eV, keV	–
Extreme ultraviolet (EUV)	nm	eV, keV	–
Vacuum ultraviolet (VUV)	nm	eV	–
Ultraviolet light (UV)	nm	eV	–
Visible light (VIS)	nm	eV	–
Near infrared (NIR)	nm, µm	eV, meV	cm^{-1}
Mid-infrared (MIR)	µm	–	cm^{-1}
Far infrared (FIR)	µm	–	cm^{-1}
Terahertz (THz)	µm, mm	–	THz
Microwaves	mm, m	–	MHz, GHz
Radio waves	cm, m, km	–	kHz, MHz

at 1730 wavenumbers corresponds to a C=O stretch in infrared spectroscopy" (Section 3.4 for more on infrared spectroscopy).

As shown in Table 1.3, different energy regimes are associated with different physical phenomena in atoms, molecules, and solids. Therefore, one can use different optical techniques associated with different energy regimes to ask different questions of a sample.

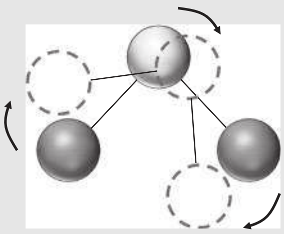
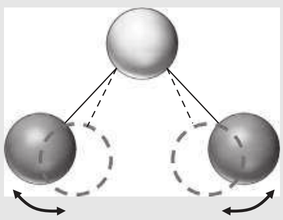
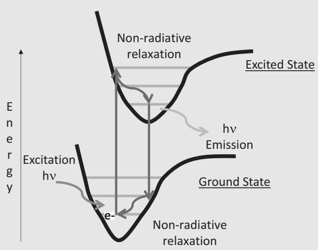
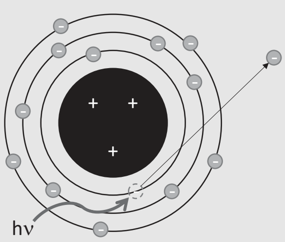
TIP: Note that Naomi Halas' group at Rice University hosts a truly fantastic tool to convert between the various energy (eV), frequency (cm^{-1}, Hz, GHz, THz), and wavelength (nm, µm) units. As of press time for this book, it can be found at: http://halas.rice.edu/conversions.

1.3 Polarization

Polarization refers to the direction of the electric field. Often, the polarization of light has an effect on the interaction with the sample, and some attention should be paid to the polarization of the light when setting up a new optical system.

In unpolarized light (also known as randomly polarized light), the electric field does not have a specific orientation with respect to the laboratory. Unpolarized

Table 1.3 Energy regimes for physical phenomena in atoms, molecules, and solids.

Physical phenomenon	Typical energy regime and units	Technique (section)
Molecular rotation and torsion 	< ~250 GHz	Microwave spectroscopy (Not covered in this book)
Molecular and lattice vibration and rotation 	10–5000 cm^{-1} (~0.001–1 eV)	(Fourier transform) infrared spectroscopy (3.4) Raman spectroscopy (3.5)
Electronic transitions 	1–10 eV (150–1240 nm)	UV-VIS-NIR spectroscopy (3.1) Fluorescence spectroscopy (3.2) Photoluminescence (3.3) Ultrafast spectroscopy (3.8)
Core electron excitation and ejection 	>10 eV	Photoelectron spectroscopy (Appendix 1)

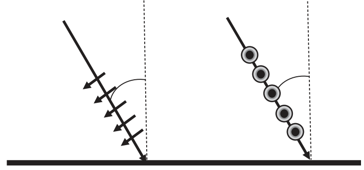


Figure 1.3

Polarization of light refers to the direction of the electric field. In P-polarized light the electric field is in the plane of the page and "plunges" into the surface. In S-polarized light the electric field is in and out of the page and "skips" on the surface.

light can be made linearly polarized with a polarizer (Section 2.3.14). Unpolarized light can also become partially polarized as it travels through a series of mirrors. In experiments where polarization is important, a "scrambler" (Section 2.3.16) is placed in the beam to restore a truly random polarization. Some optical components such as diffraction gratings in spectrometers have different throughput efficiencies for different polarizations of light.

Scientists describe the polarization of light by the letters S and P for historic reasons, using abbreviations from German terms for parallel and perpendicular. In P-polarized light, the polarization is perpendicular to the surface on which light is incident (in the plane of the page in Figure 1.3). In S-polarized light, the polarization is parallel to the surface (in and out of the page in Figure 1.3). A commonly used mnemonic is that in P-polarized light the electric field "plunges" into the surface, while in S-polarized light the electric field "skips" off the interface.

Linear polarization (sometimes called **plane polarization**) means that the orientation of the electric field with respect to the lab does not change as the light propagates (Figure 1.4).

Lasers are almost always linearly polarized at their output and the orientation of the electric field is usually set up to be either parallel to the plane of the optical table or perpendicular to the plane of the optical table. The polarization of the light can be flipped between S and P polarizations with mirrors arranged in a folded periscope configuration (Section 5.5) or with a half-wave plate (Section 2.3.15).

The electric field of the light is a vector that can be decomposed into x and y components. An **anisotropic** material can have different indices of refraction for the x direction and the y direction, meaning light will travel at different speeds in the two directions of the material. This will introduce a phase delay on one of the vector components of the electric field.

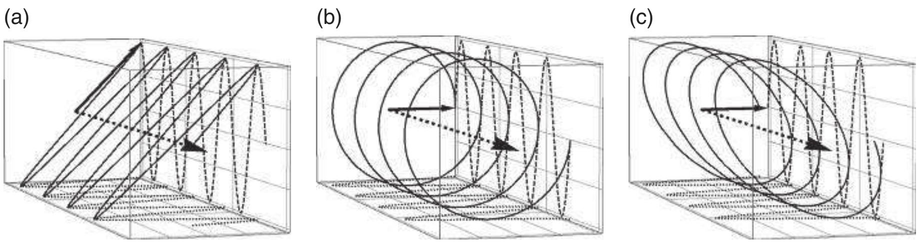


Figure 1.4

The solid arrows denote the direction of the electric field. The solid lines show how the direction of the electric field changes as the light propagates. The dotted arrows show the direction the light is traveling. The dotted and dashed lines depict how the *x* and *y* vector components of the electric field vary as the light travels. (a) Linearly polarized light means that the electric field direction does not change orientation with respect to the lab as the light propagates. The vector components of the electric field are in phase. (b) Circularly polarized light means the direction of the electric field rotates as the light propagates past a fixed point in the lab. The vector components of the electric field are out of phase by $\pi/2$ for circularly polarized light. (c) In elliptically polarized light, the orientation of the electric field spends more time in one direction than another as it rotates. The vector components of the electric field are out of phase for elliptically polarized light. The degree of the phase difference changes the ellipticity of the electric field.

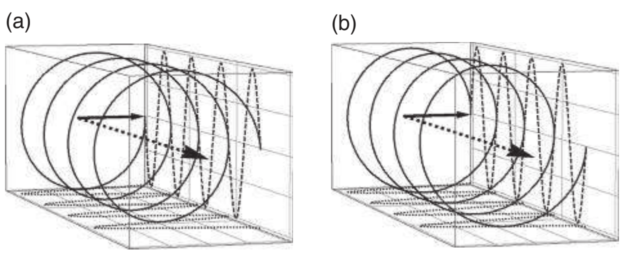


Figure 1.5

The solid arrows denote the direction of the electric field. The solid line shows how the direction of the electric field changes as the light propagates. The dotted arrow shows the direction the light is traveling. The dotted and dashed lines depict how the *x* and *y* vector components of the electric field vary as the light travels. The relative phase delay between the vector components can determine if the electric field will rotate clockwise or counterclockwise as the light travels. (a) In right-handed circularly polarized light, the electric field rotates clockwise. (b) In left-handed circularly polarized light, the electric field rotates counterclockwise.

If one direction is retarded by exactly $\pi/2$ relative to the other vector component, the linearly polarized light will become circularly polarized. In **circularly polarized light**, the electric field rotates around the axis of light propagation as the light travels. This means that in a given instant, the light incident on your sample will have an electric field oriented in a specific direction. But, averaged over a

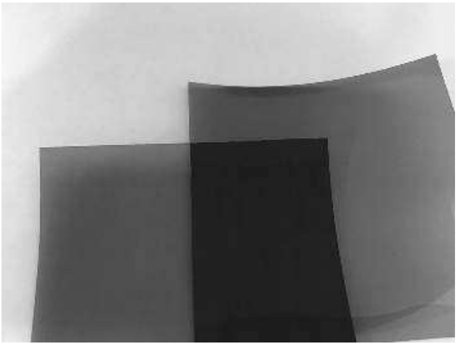


Figure 1.6

Two partially overlaid sheet polarizers. When the orientations of the polarizers are 90 degrees relative to each other, they are said to be crossed. Crossed polarizers will block all light as seen in the dark overlapping region in the middle. The single polarizer looks gray as it is blocking light of a specific polarization (about half the light in a typical unpolarized beam).

short amount of time, the sample will experience all directions of the electric field in turn as the light propagates.

If one vector component is delayed by some other amount, the light will become elliptically polarized. **Elliptical polarization** is similar to circular polarization, in that the electric field direction rotates around the axis of light propagation. However, the x and y vector components of the electric field are out of phase by a value other than $\pi/2$, so the electric field traces out an ellipse (Figure 1.4) instead of a circle.

Details of how to manipulate and control the polarization of light are given in Sections 2.3.14, 2.3.15, 2.3.16, and 5.5.

1.4 Spatial Resolution

"What is the smallest object that can be seen?" is a common first question for any imaging system. The answer is that it depends on the spatial resolution of the system. Spatial resolution is how close two objects can be and still be definitively observed as two objects. There are several mathematical definitions of spatial resolution. A commonly used definition is known as the Rayleigh criterion.

A diffraction-limited spot does not truly focus to a single point. It in fact has a series of rings around it referred to as Airy disks. The Rayleigh criterion says two points are just resolvable if the maximum of one Airy disk is at the first minimum of the other point's Airy disk.