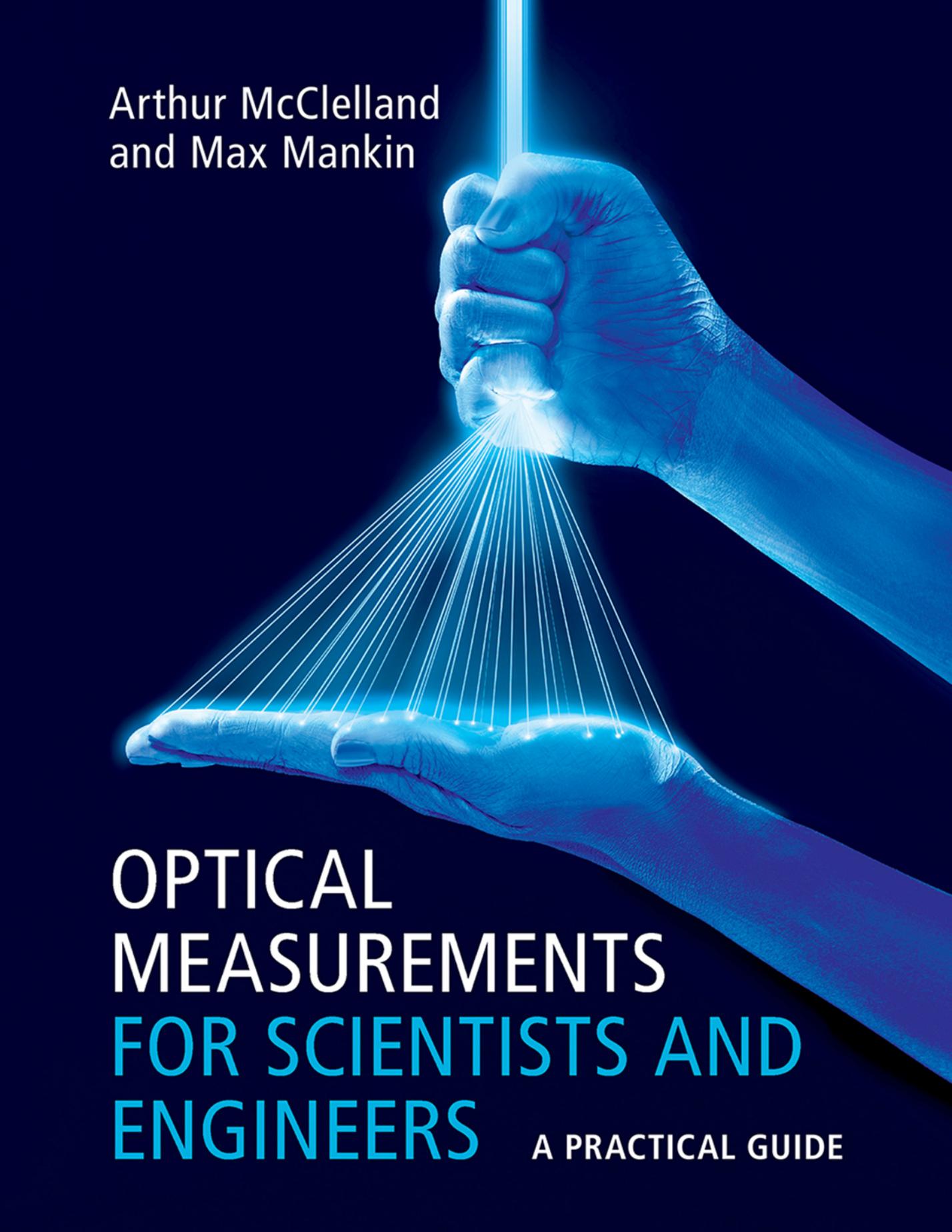


Arthur McClelland
and Max Mankin

The image features a hand at the top holding a vertical laser beam. The beam is focused onto the palm of a second hand held below it. From the point of focus, numerous thin lines of light radiate outwards, creating a fan-like pattern. The entire scene is set against a dark blue background with a subtle gradient.

**OPTICAL
MEASUREMENTS
FOR SCIENTISTS AND
ENGINEERS**

A PRACTICAL GUIDE

Optical Measurements for Scientists and Engineers

A Practical Guide

With this accessible, introductory guide, you will quickly learn how to use and apply optical spectroscopy and optical microscopy techniques. Focusing on day-to-day implementation and offering practical lab tips throughout, it provides step-by-step instructions on how to select the best technique for a particular application, how to set up and customize new optical systems, and how to analyze optical data. You will gain an intuitive understanding of the full range of standard optical techniques, from fluorescence and Raman spectroscopy to super resolution microscopy, and understand how to navigate around an optics lab, with clear descriptions given of the most common optical components and tools. Including explanations of basic optics and photonics, and easy-to-understand mathematics, this is an invaluable resource for graduate students, instructors, researchers, and professionals who use or teach optical measurements in laboratories.

Arthur McClelland is a Principal Scientist at the Center for Nanoscale Systems at Harvard University. He is a member of the American Chemical Society and the New England Society for Microscopy, and has co-taught Harvard Extension School's *Introduction to Microscopy* course.

Max Mankin is the Co-Founder and CTO of Modern Electron, USA, and completed his PhD at Harvard University.

Spectroscopy and Microscopy are two important fields in today's technology. *Optical Measurements for Scientists and Engineers* provides an excellent introduction to these fields with a very practical point of view. The book is very well illustrated and explained; and it limits the number of equations used. Thus *Optical Measurements for Scientists and Engineers* is within the reach of a wide audience. Of course, the emphasis is on optical measurements, which are a critical aspect in applied technology.

José Sasian, *University of Arizona*

Optical Measurements for Scientists and Engineers

A Practical Guide

Arthur McClelland

Harvard University, Massachusetts

Max Mankin

Harvard University, Massachusetts



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For Simon, Tobi, and Lisa.
Thanks for being patient while I wrote a book.
A. M.

To my parents and my sister, who by example
taught me the value of hard work and the importance
of passion for one's pursuits.
M. M.

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Preface

Experiments involving lasers, light, and optics are ubiquitous in virtually every field of experimental science and engineering. Recently, advanced optical characterization techniques have begun to pervade the life sciences and medical fields as more physical scientists are turning their attention to biological questions. There is still a strong “build it yourself” culture in optics and, unfortunately, graduate students and postdocs often find themselves suddenly in charge of a lab full of expensive optics that they are totally unfamiliar with. This book is meant as a crash course “What is that thing?”-type guide, complete with practical tips and tricks to help get optical setups built and collecting data. It focuses on the most common components used in optical spectroscopy and microscopy setups and it is by no means exhaustive. It is, of course, biased by the authors’ own experiences in various academic optics labs but it is hoped that it will help the reader feel more comfortable in the lab, dispel some of the incorrect lab lore that is often passed down through the years, and result in better (and easier!) science at the end of the day.

Is this book right for you? We’ve written the text for biologists, chemists, materials scientists, applied physicists, electrical engineers, and medical professionals, and purposefully limited the theory and the math in favor of diagrams, pictures, tips, tricks, and quick, practical information that will help you get your measurement done without earning a second degree. To understand everything in this book, you’ll only need a little algebra and trigonometry, an understanding of 45 and 90 degree angles, and maybe an introductory chemistry or physics course.

Perhaps you have encountered one of the following scenarios:

- You are asked to “Build a photoluminescence spectroscopy system” but you’ve never turned on a laser, let alone aligned a laser beam, mirrors, and lenses.
- Total internal reflectance microscopy sounds just perfect for characterizing your cells, but you don’t know what such a microscope looks like or which vendors to buy the components from.
- You see a complicated graph in an exciting seminar and everyone is talking about it but you have no idea how to even begin interpreting all of the contour lines and symbols.

- You find an unlabeled, dirty filter on your laser table and the previous student (who has now graduated, moved 6000 miles away, and started a bakery) hinted some time last year that maybe it's the one that you need for your new measurement. How do you figure out what it is?
- Everyone seems to be speaking another language referring to lots of things in optics lab that just sound like gibberish to you. Can you please hand them the what?!

We, the authors, have experienced situations like these, so we wrote this book thinking about our experiences and state of mind when we first started working with laser tables and optics. A practical guide like this would certainly have saved us from many late nights of bad measurements and frustration with laser alignment. We hope it will be helpful to you and your science.



Acknowledgments

As with any major undertaking, there are many people whose contributions have led to this book, sometimes knowingly and sometimes unknowingly. I apologize in advance to anyone I inadvertently leave out. It has been an exciting time to be involved with spectroscopy and microscopy, and I look forward to what the future holds.

I started experimenting with lasers by making holograms and exploring optics in general at a summer science camp in Morgantown, WV, circa 1993. Thanks to my parents Christine and Steve McClelland for letting me enroll in the science summer camp. Thanks to Judy Werner for doing the thankless job of organizing the summer camp every year, and a special thanks to Sean Lalley for letting a bunch of middle schoolers play with lasers and develop holograms. Lasers in those days were expensive and often somewhat homebuilt. In retrospect, it was an amazing effort on his part to organize the hands-on making of holograms by kids.

In college I was fortunate enough to work in a number of research groups with quite a number of very patient graduate students and postdocs. Thanks to Sava Denev and Professor David Snoko for my first summer research experience in an optics lab at the University of Pittsburgh. Thanks to Vasiliy Fomenko for his infinite patience in teaching me how to realign a Ti:sapphire laser after I had messed it up yet again, and Professor Eric Borguet for giving me the opportunity to do an undergraduate research thesis in his lab in ultrafast optics at the University of Pittsburgh. Thanks to the Applied Physics program at the University of Michigan for support to explore different areas of research. Thanks to Professor Steve Yalisove for time in his group. Thanks to Jie Wang for the patience while teaching me how to realign an OPO/OPA/DFG system for SFG-VS spectroscopy. Thanks to Professor Zhan Chen for overseeing my PhD thesis at the University of Michigan. Thanks to Abdelkrim Benabbas and Professor Paul Champion for my postdoctoral experience at Northeastern University.

Thanks to Eric Martin and Fettah Kosar for hiring me and giving me a chance to grow professionally at the Center for Nanoscale Systems at Harvard University. Thanks especially to Fettah for getting the Introduction to Microscopy course for the Harvard Extension School off the ground, as large sections of this book grew out of lectures and discussions from this course. Thanks to David Bell, Bill Wilson, Greg Lin, and all my other CNS colleagues for their continued support.

Thanks to all the users of CNS who bring me new scientific challenges to think about every single day.

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Thanks to Mac Hathaway and Andy Boughton for giving critical feedback on the manuscript. Thanks to Cambridge University Press for being patient while we worked on this book around our day jobs and family commitments.

Finally, thanks to my co-author Max Mankin who made the hypothetical idea of writing this book a reality with his infectious enthusiasm.

Arthur McClelland

When I started graduate school, I had never worked in an optics lab before. There were lots of people who helped me learn my way around a laser table.

First, thanks to my co-author Arthur McClelland, who taught me optics, tolerated countless uninformed questions, and humored my suggestion to write a book to help others who wanted to use optical techniques without much of a background in it. Arthur served as a constant resource, inspiration, and friend in using optics for my research.

Second, I owe my PhD adviser Professor Charles M. Lieber a big debt of gratitude for figuratively throwing me in the deep end of the world of optics in one of my first graduate school projects. I learned by doing! Professor Lieber was also generous enough to provide me opportunities to learn from experts in this area, including Professor Ritesh Agarwal at the University of Pennsylvania and his accommodating and patient student Dr. Carlos Aspetti, and Professor Hongjie Dai at Stanford. During that trip to Stanford, I worked with Dr. Guosong Hong for the first time. Guosong patiently tolerated my rudimentary understanding of infrared optics and photonics and very quickly got me up to speed. I'm enormously thankful for the opportunities to learn from experts that I had during this time.

I was also lucky enough at the time to have fantastic mentors and experienced laser jocks to constantly pester with questions. Thank you to my fantastic

colleagues Dr. Robert Day, Dr. Ruixuan Gao, Dr. Guosong Hong, Professor Thomas Kempa, Professor Bozhi Tian, Professor James Cahoon, Dr. Jinlin Huang, and Dr. Carl Barrelet, who helped me navigate my journey from zero to one around a laser table, doing everything from teaching me about how to build and automate measurement setups to identifying unlabeled filters and lenses.

I also owe special thanks to Professors Hong-Gyu Park, Sun-Kyung Kim, and You-Shin No, collaborators and true optics and photonics experts who patiently spent many coffee breaks and late evenings explaining the principles of optics and photonics to me.

I also owe an enormous thanks to my thesis committee members and mentors Professor David Bell and Professor Cynthia Friend, as well as the Harvard Center for Nanoscale Systems staff, including Adam Graham, Greg Lin, Fattah Kosar, Andrew Magyar, and Steve Hickman for their constant support and early introductions to many of the techniques listed in this book. Thanks as well to Professors Conor Evans and Ed Boyden, whose enthusiasm and deep understanding of optics in biology was educational and inspirational. I also owe early inspiration and education in the principles of physical chemistry and optics to Brown Professors Shouheng Sun, Jimmie Doll, Eunsuk Kim, my mentor Dr. Vismadeb Mazumder, as well Professors Krysta Ryzewski, Brian Sheldon, and Susan Alcock, who served as inspirational mentors in testing cultural heritage artifacts using optical and other analytical techniques.

Finally, thank you to all of my friends, colleagues, and family who encouraged me to write this book! Hearing from you about your experiences in optics and photonics labs informed the contents, writing style, and level of detail that we hope will make this a useful manual for everyone out there who needs to use optical characterization for their science, engineering, and analysis.

Max Mankin



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

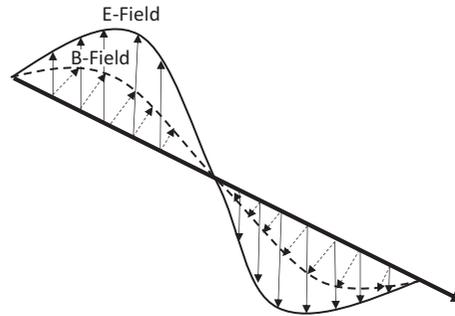


Figure 1.1

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.

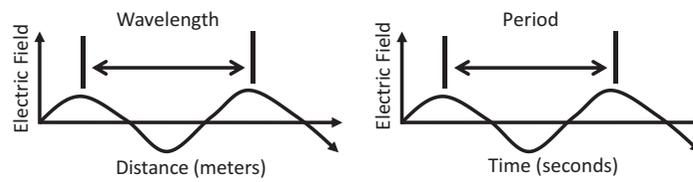


Figure 1.2

Waves can be described in terms of either wavelength or frequency, which equals $1/\text{period}$.

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 “ $h\nu$ ” 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 – 3.7×10^8 MHz	What you see
Near infrared (NIR)	800–3000 nm	0.413–1.55 eV	3.7×10^8 – 1.0×10^8 MHz	Night vision goggles
Mid-infrared (MIR)	3–25 μ m	50–413 meV	1.0×10^8 – 1.2×10^7 MHz	Heat/thermal imaging
Far-infrared (FIR)	25–50 μ m	25–50 meV	1.2×10^7 – 5.88×10^6 MHz	Rarely used
Terahertz (THz)	10 μ m–1 mm	124–1.24 meV	0.3–30 THz	Medical imaging, security
Microwaves	1 mm–1 m	1.24 meV–1.24 μ eV	300 MHz–300 GHz	Wi-Fi, cell phone communications
Radio waves	>1 m	<1.24 μ eV	<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.

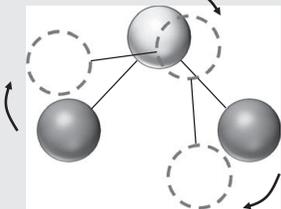
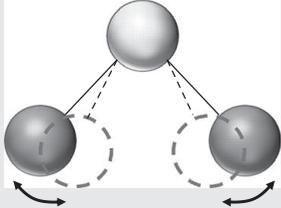
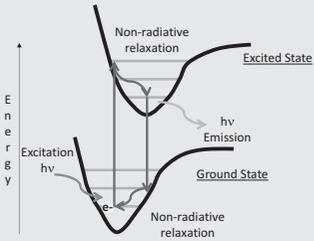
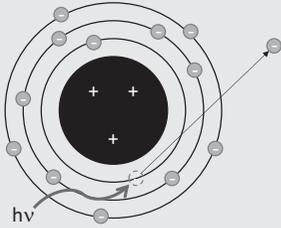
TIP: Note that Naomi Halas’ group at Rice University hosts a truly fantastic tool to convert between the various energy (eV), frequency (cm⁻¹, Hz, GHz, THz), and wavelength (nm, μm) units. As of press time for this book, it can be found at: <http://halas.rice.edu/conversions>.

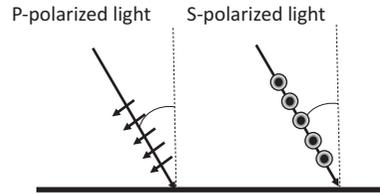
1.3 Polarization

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 	$< \sim 250 \text{ GHz}$	Microwave spectroscopy (Not covered in this book)
Molecular and lattice vibration and rotation 	$10\text{--}5000 \text{ cm}^{-1}$ ($\sim 0.001\text{--}1 \text{ eV}$)	(Fourier transform) infrared spectroscopy (3.4) Raman spectroscopy (3.5)
Electronic transitions 	$1\text{--}10 \text{ eV}$ ($150\text{--}1240 \text{ nm}$)	UV-VIS-NIR spectroscopy (3.1) Fluorescence spectroscopy (3.2) Photoluminescence (3.3) Ultrafast spectroscopy (3.8)
Core electron excitation and ejection 	$> 10 \text{ eV}$	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.

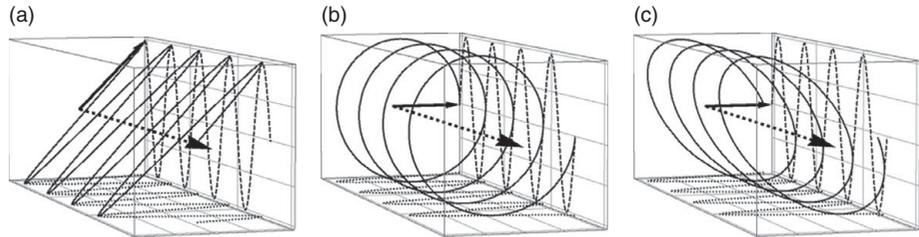


Figure 1.4

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.

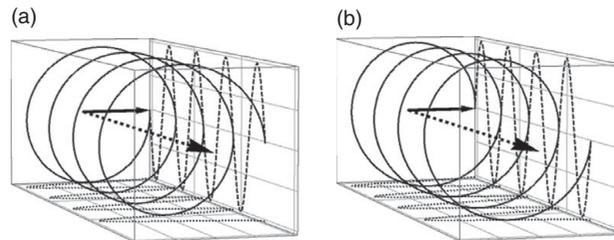
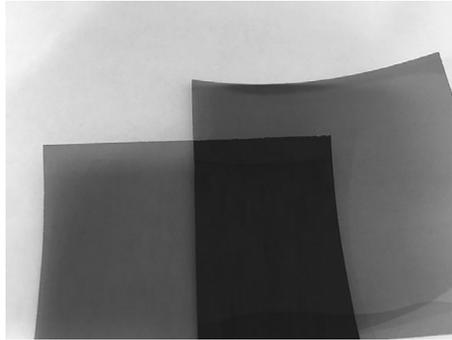


Figure 1.5

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.

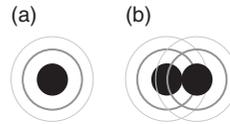


Figure 1.7

(a) Cartoon representation of an Airy disk formed by diffraction limited focused spot. (b) Two Airy disks at the Rayleigh criterion limit of resolvability.

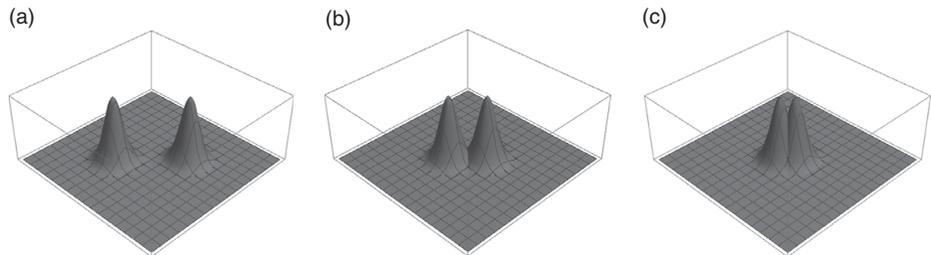


Figure 1.8

(a) Two fully resolved points. (b) Two overlapping but resolvable points. (c) Two unresolvable points.

Light with shorter wavelengths can probe smaller features. Resolution limits can be expressed quantitatively as a **diffraction limit**, d , which describes the smallest feature that it is physically possible to observe using light of a given wavelength, λ :

$$d = \frac{\lambda}{2n \sin \theta} \sim \frac{\lambda}{2} \quad (1.3)$$

This limit was first described by Ernst Abbe in 1873. For instance, visible light (wavelength ~ 500 nm) has a diffraction limit ~ 250 nm. Therefore, it is possible to resolve features such as bacteria, cells, hair, and 1980s transistors ($\sim 1\text{--}100$ μm), but not modern transistors, viruses, or cell walls ($7\text{--}200$ nm). To achieve higher resolution, one can use smaller wavelengths of light for imaging (e.g., UV or x-ray).

There is an important distinction between detection limit and resolution limit. Objects smaller than the resolution limit can be detected, but their spatial position cannot be localized less than the diffraction limit. For instance, a single fluorescent molecule ($1\text{--}2$ nm in length) can be detected, but the position cannot be determined with far-field optical means to better than ~ 200 nm. Several super resolution microscopy techniques have been developed to get around this limit. They are discussed in detail in [Sections 4.13–4.17](#).

1.5 Near-Field and Far-Field

The rules surrounding diffraction limit and resolution apply in the case known as **far-field**, which is that the optical element is $> \sim 1-2$ wavelength distances away from the object of interest. One can exceed the diffraction limit using **near-field** techniques, in which an object is effectively $\sim < 1-2$ wavelengths away from an optical element. Near-field techniques often involve a scanning probe approach. For example, the probe can be a tapered optical fiber that is metal coated and has a sub-diffraction limit aperture at the tip to allow an evanescent electric field of the light to leak out. Since the aperture is smaller than the diffraction limit, the light cannot propagate through the hole. With this approach, you have a localized electric field from the light that you can scan around the sample and test the sample localized electric field interactions.

The coupling of light into these scanning near-field optical microscope (SNOM) tips has proved hard enough that a new approach of scattering the light off the outside of a metal-coated atomic force microscopy tip and using a lock-in amplifier to separate the near-field and far-field is gaining popularity. This technique is referred to as scattering scanning near-field optical microscopy (S-SNOM), and is briefly described in [Section 3.4.15](#).

1.6 Light–Matter Interactions

When light encounters solids, liquids, and gases, it can travel through (**transmission**), bounce off (**reflection** and **scattering**), or be taken up by a material (**absorption**).

We describe transmission and reflection by a quantity known as the refractive index, often written as n . Refractive index can be thought of qualitatively as how fast light can propagate through a material relative to the speed of propagation through vacuum. For instance, air has a refractive index of ~ 1 whereas water has a refractive index of ~ 1.33 . This means that light travels 33 percent slower in water than in air. Glass has an index of refraction of around 1.5, which puts a limit on the speed of fiber optic communication.

Whenever light encounters an interface between materials with two different indices of refraction, some light will be reflected (bounce back) and some will be refracted (travel into the material but with a bend in the direction of propagation). The angle at which the light will be refracted is described by “Snell’s law”:

$$n_1 \sin \theta_1 = n_2 \sin \theta_2 \quad (1.4)$$

where n_1 and n_2 are the refractive indices of material 1 and material 2, respectively, and θ_1 and θ_2 are angles from the surface normal describing the direction from which the light propagates ([Figure 1.9](#)).

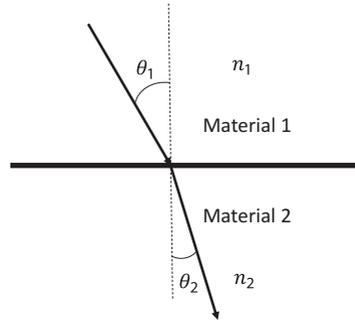


Figure 1.9

Snell's law describes how the direction of propagation of light will change when it encounters a material with a different index of refraction.

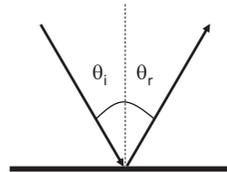


Figure 1.10

In specular reflection the angle of incidence θ_i is equal to the angle of reflection θ_r .

1.7 Reflection

When light reflects off a surface the angle of incidence (θ_i) is equal to the angle of reflection (θ_r).

In a dielectric (non-electrically conductive) material (e.g., a piece of glass) the amount of light that is reflected or transmitted is determined by the Fresnel equations:

$$R_p = |r_p|^2 = \left| \frac{\tan(\theta_i - \theta_t)}{\tan(\theta_i + \theta_t)} \right|^2 \quad (1.5)$$

$$R_s = |r_s|^2 = \left| \frac{\sin(\theta_i - \theta_t)}{\sin(\theta_i + \theta_t)} \right|^2 \quad (1.6)$$

$$T_p = |t_p|^2 = \left| \frac{2 \sin \theta_t \cos \theta_i}{\sin(\theta_i + \theta_t) \cos(\theta_i - \theta_t)} \right|^2 \quad (1.7)$$