SEEING THE LIGHT

OPTICS WITHOUT EQUATIONS

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The Author

William L. (Bill) Wolfe is professor emeritus at the James C. Wyant College of Optical Sciences of the University of Arizona. He taught optics there, with an emphasis on infrared techniques and radiometry, for twenty-five years and has been retired for about that long. He spent three years at the Honeywell Radiation Center in Lexington, MA just before that, where he managed the Electro-optics Systems Department and taught part time at Northeastern University. His first real job (not counting delivering papers and pollinating lilies) was at The University of Michigan where he taught in the Electrical Engineering Department and did research at the Environmental Research Institute, then the Willow Run Labs.

He was awarded a BS in Physics by Bucknell University in 1953 an MS in Physics in 1955 and an MSE in electrical Engineering by The University of Michigan in 1965.

He was married for 60 years to his lovely and very supportive wife, Mary Lou. They raised three incredible children who became a doctor, financial planner and aerospace engineer and are now retired. He now has six grandchildren making their way in the world and through college. He has written books on *Infrared System Design*; *Infrared System Design Examples*; *Radiometry*; *Imaging Spectrometers*; *Optics Made Clear*; *Rays, Waves, and Photons, a compendium of historic foundations and emerging technologies of pure and applied optics*, and *40 Fun-filled Float Trips for Fly Fishers.* He co-authored a book much earlier in 1964, *Fundamentals of Infrared Technology* with Marvin Holter, Sol Nudelman and Gwynn Suits. He edited *Optical Engineer's Desk Reference, Handbook of Military Infrared Technolog*y in 1965 and *The Infrared Handbook* in 1978 with George Zissis. He was a co-editor of the second edition of *Handbook of Optics*.

He is a Fellow of both the Optical Society and SPIE. He served on the Board of Directors of the Optical Society and was President of SPIE in 1989. He received its gold medal in 1999.

He was selected Most Successful in His Chosen Career by Bucknell University in 2004.

He served as an advisor to many government agencies and consultant to many companies. His favorite hobby is fly fishing, and some of that shows up here and there in this book. He solves a crossword puzzle now and then, although he tries many. He is still sharing his enthusiasm for optics with members of the Osher Lifelong Learning Institute, the Tucson Academy, Rotary – and whomever else will listen – by regaling them with some of this information.

He is most proud of the fact that he helped 50 young people attain their graduate degrees in optics at the James C. Wyant College of Optical Sciences.

Chapter 1

Optical Phenomena

This chapter on the phenomena of optical processes discusses the nature of light and its behavior. We really do not know what light is, but we know what it does. It reflects, refracts, diffracts, interferes, scatters, absorbs, propagates, changes its wavelength with motion, comes and goes, and does it in the shortest time. These topics are covered in this chapter in about that order and in more detail. Their understanding is required for many of the applications discussed in other sections.

Light is a transverse wave motion that vibrates in directions perpendicular to its direction of travel. The direction of that vibration—vertical, horizontal, or otherwise—is its **polarization** direction. **Reflection** is the return of light back in the general direction from which it came. It can be specular or diffuse and high or low. **Refraction** is a change in the direction of propagation of light when it goes from one medium to another, often thought of as bending of light. It is a result of the fact that light goes slower in denser media. **Diffraction** is the spreading of a beam of light when it encounters an aperture or an obstacle. **Interference** is the combining of two or more beams of light that then produce an enhanced or reduced amount of light. **Absorption** of light is the process of transferring the energy of the light to that of the material. It heats it or changes its electronic configuration. **Emission** is the opposite of absorption, that is, the transformation of energy in a material into light. **Propagation** is the way light gets from one place to another. We all know about the speed of light being the fastest thing there is, but it slows down in materials. The change of the wavelength of light with the motion of the source or receiver is called the **Doppler effect** and is more familiar with acoustic waves. In optics and especially in astronomy, the Doppler effect is known as the **red shift** since it is most often observed in stars that are rapidly moving away. And there is a property of light that minimizes its travels. Light is either lazy or efficient, depending upon your point of view. It takes the path of minimum time. Light is fair; it believes in **reciprocity**. What goes out comes back and in much the same way.

Reflection from metals and other conductors of electrons and electric current is much more complicated. The reflected radiation is often elliptically polarized. The wavefronts are complex. In general, it is messy in detail and extremely complicated to calculate. Fortunately, it is not necessary to do so for almost all optical applications. Metals are mostly used for vanity mirrors, automobile mirrors and astronomical mirrors. They only require high reflectivity.

1.5 Interference

Interference is a wave effect. It is the result of waves combining in a way that they add or subtract with each other to make more or less light in that region. Forget the photons for these concepts.

We can start with an idealized situation for simplicity. Imagine a perfect, single frequency wave, shown in red in Figure 1.5.1. It has a frequency, wavelength and amplitude as described in Section 1.1.

Figure 1.5.1 Single sine wave.

When it combines with another wave, like the one in phase with it shown in blue in Figure 1.5.2, the two amplitudes add, and the result is a wave of twice the amplitude, shown in green. When two waves that are exactly out of phase add, the result is nothing. They cancel each other, as shown in Figure 1.5.3. When the two waves are somewhat out of phase, the result is a diminished, resultant wave, shown in Figure 1.5.4.

The two oxygens can move in and out together in the same direction as indicated on the first row, or they can move in and out in opposite directions, depicted in the second row. The two oxygens can also go in opposite directions. There are more such motions, (like in and out of the paper), but this is enough to show the principle. These occur at frequencies of 2.2×10^{13} and 8×10^{12} cycles per second (Hertz) (among others), which corresponds to wavelengths of 4.5 and 12 μm, well-known absorption regions of carbon dioxide. The absorptions and emissions occur at optical frequencies that correspond to the natural frequencies of these motions. This is representative of molecular absorption and emission. Other molecules have other motions, molecular and atomic weights, binding energies and frequencies. Complex molecules have complex spectra of vibrations and rotations. It is what makes all of them unique.

When light is incident upon any one of these materials, it interacts with the electrons or molecules. If there is a resonance, there is absorption. If not, the light continues on. This is one way to understand why light goes slower in these media.

I hope you agree that this has been an absorbing discussion!

1.9 Propagation

The propagation of light, that is, radiation transfer, is the process of light traveling from a source through various media to a receiver. It is basic to the calculation of measurements and the performance of cameras, telescopes and other optical receivers—as well as the heat balance of our planet.

It is necessary to start with the definitions of a few terms and their symbols. **Power**, with the symbol P, is the number of watts radiated by some source. It is **energy** U per unit time t. Power per unit area is called power or **radiation (areal) density**, and it is called irradiance or radiant **incidence** E if it is received by a surface (not incidence). It is radiant emittance or **exitance** M if it is emitted. It has units of watts per square meter or per square foot, or equivalent area measurement. Power per unit solid angle is called radiant **intensity** I and has units of watts per steradian (see below for an explanation of solid angle). Power per unit area and per unit **solid angle** is called **radiance** or

1.13 Resolution

Resolution is the discernment of things, determining that there are two closely spaced lines and not just one blurry one or that there are two closely spaced audible beeps and not one long one. In optics, there are three types of resolution: spatial, spectral and temporal. Resolution is also the agreement of an argument or a strong intention.

I hope you have the resolution to wade through this.

Spatial resolution is usually determined by the discernment of two or more closely spaced lines or two or more points with a given contrast. The contrast is usually stated either as contrast in a specific sense or as modulation. The input lines or points have full contrast, black on white; the output may be some shades of gray. Contrast has at least two definitions: the difference between the maximum and the minimum divided by either the average or the sum of them. Modulation is the difference divided by the sum.

Chapter 2

Optics in Nature

Light is all around us in nature: blue skies, red sunsets, mirages, and more. This chapter describes the concepts underlying the more familiar of them. But there are many more. They include why leaves turn color in the fall, how chameleons know to change their colors and how they do it, and how migratory birds find their way. These are described in the classic book *Rainbows, Halos, and Glories* by Robert Greenler[1] and elsewhere online.

As you will discover, blue skies are created by the spectrally differential scattering of small particles. Red sunsets are created in the same, but somewhat opposite, way and are enhanced by spectrally uniform scattering of the large particles in clouds. Sunsets are more vivid in the American Southwest, where the air is drier.

Hummingbirds turn their better sides to us and show us different colors by virtue of the interference properties of the layers of their feathers.

Rattlesnakes and pit vipers find kangaroo rats because the rats are warm blooded. Mosquitos find us because we exhale warm carbon dioxide.

2.1 Blue Skies

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[1] Greenler, R. *Rainbows, Halos, and Glories*. SPIE Press (2020) and Cambridge University Press (1990).

2.4 Hummingbirds

Hummingbirds (or "hummers" for short) whir their wings to hum at us, and they also flash their varying colors to please us—and maybe to entice or impress other hummers. As I am sure you have noticed, the colors seem to change as the birds change their positions with respect to the sun. This is the result of optical interference.[3] Hummers have layers of feathers on the outer portions of their bodies. These layers give rise to interference. The feathers themselves are brownish gray. From one viewpoint, the layer thickness is exactly a full wavelength of light, thereby generating constructive interference (e.g., for red light, as shown in Figure 2.4.1), but as the bird's position relative to the sun changes, the effective thickness can shorten and become exactly a full wavelength for blue light, as in Figure 2.4.2.

Figure 2.4.1 He's red.

Figure 2.4.2 No, he's blue (or blue green).

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[3] Greenewalt, C., Brandt, W., and Friel, D. "The iridescent colors of hummingbird feathers," *Proc. Amer. Philo. Soc.* **104**(3), 249–253 (1960).

2.7 Mosquitoes

Who needs them? But they are here. Not so much in Arizona, where it is very dry and there are few places for them to breed. I think it is well known that the female of the species is the only one who bites. Not so well known is that it is the *pregnant* female who bites. She is after food for her new expected young and her own nourishment needs.

Mosquitoes home in on warm carbon dioxide from about 30 feet away. One countermeasure is to not exhale – ever. Inhaling is okay; exhaling is not! As mosquitoes get closer, they home in on various odors on the skin. One advertised repellant is the sound of an amorous male mosquito. I have no idea how they determined the sound or replicated it.[7] The online recommendations of how well it works are mixed.

2.8 Pit Vipers

These reptiles are a species of snakes that includes sidewinders and other rattlesnakes. They have small pits in their cheeks that act as pinhole cameras

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[7] Amazon. "William and Joseph Mosquito Annoyer reviews," https://www.amazon.com/William-Joseph-Mosquito-Annoyer-Grey/dp/B000KNE47C.

single spider strand outside my window. It is the same kind of spectral refraction seen in rainbows.

2.10 Sundogs and Halos

Sundogs are parts of full halos around the sun. They are formed in almost the same way as rainbows, but they arise from the interaction of sunlight with ice crystals.[12] They might be called icebows. Rather than refracting and reflecting from water droplets, as in rainbows, the light is refracted and reflected from tiny ice crystals in the upper atmosphere (where it is cold

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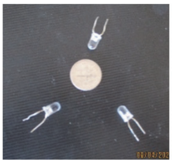
[12] Greenler, R. *Rainbows, Halos, and Glories*, SPIE Press (2020) and Cambridge University Press (1990).

Chapter 3

Optical Components



This chapter describes the individual optical elements that are used to make optical instruments. Everyone would agree that a light-emitting diode (LED) is an optical component, a single optical component. But it gets more arguable when you deal with prisms and lenses. A device called a prism is sometimes the combination of one or two individual prisms, but we still deal with it as a single prism. The same is true for lenses—a doublet lens is still considered a lens.

These are what I consider components: LEDs, baffles, blackbodies, and even lenses and prisms.

3.1 Baffles

The process is to insert vanes to cause as many reflections as possible from the sides of the baffle tube to the mirror without restricting the light from the object to be sensed.

These are the concepts of baffle design.[2] The details can get much more complicated.

There are several computer programs available for the design of these baffles, notably GUERAP and ASAP.[3] One of my students applied ASAP to the improved performance of the Sidewinder missile optical guidance head.[4] She reduced the scatter to the detector by several orders of magnitude. The design of the Sidewinder infrared guidance is discussed further in Section 4.28.

Although baffle design seems straightforward and may not be very interesting, it was a considerable bone of contention in the design of the optical device that communicated between the first Apollo lander, the LEM, the Lunar Excursion Module, and the Apollo orbiter.[5] It has also been critical in the design of many of anti-ICBM detectors.[5]

3.2 Beam Splitters

There are beam splitters, and there are beam splitters. They all divide, split, an incident beam in some way. Some divide it spatially—they split light into two separate parts. Some divide it in amplitude. They send a portion of the intensity of the beam in one direction and the other portion in another direction. Some divide it into different polarizations.

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[2] Fest, E. *Stray Light Analysis and Control*, SPIE Press (2013) [doi: 10.1117/3.1000980].

[3] *GUERAP II -Users Guide,* Defense Information Technical Center (1974), online; *About ASAP, The Breault Optical Design Program*, online.

[4] Fender, J. "An Investigation of Computer-Assisted Stray Radiation Analysis Programs," Dissertation, The University of Arizona (1981).

[5] Personal experience.

3.6 Diffractions Gratings

Diffraction gratings are a means of generating spectra. They are a substitute for, and usually an improvement to, prisms. Their performance may be understood by first considering how a double slit produces an interference pattern because gratings combine diffraction and interference from multiple slits.

When monochromatic light impinges on two slits, each performs as a new source and propagates the light in spherical waves (shown as circles in Figure 3.6.1). These are sets of spherical crests and troughs shown as red and blue, respectively, in Figure 3.6.1. Where a crest meets a crest, there is constructive interference (red on red), and where a crest meets a trough (red on black), there is destructive interference; thus, there is an alternating bright and dark pattern of light, i.e., an interference pattern. And it is a function of wavelength.

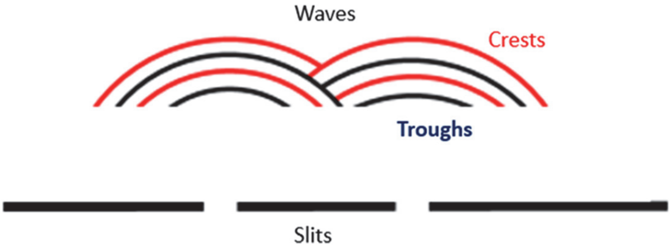


Figure 3.6.1 Double-slit interference.

If more slits are introduced, the waves add in the same way. Where the crests meet, there is constructive interference, and where the troughs meet the crests or other troughs, there is destructive interference. And a fourth, and a fifth, and so on, as illustrated in Figure 3.6.2 and indicated by the horizontal blue line.

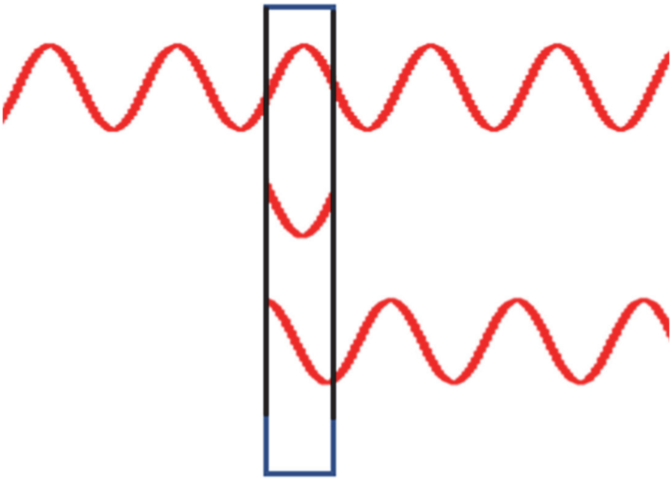
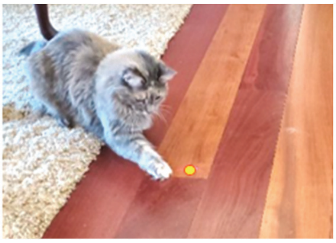


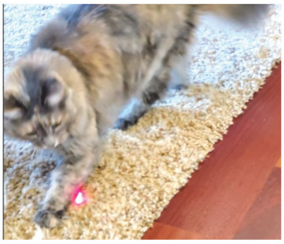
Figure 3.8.8 A QWOT interference illustration.

The design of interference filters is much like the design of lenses. There are computer programs that perform this task in much the same way that lenses are designed. An online site lists and provides links to several such design programs.[27] Some are free.

A special kind of filter is known as the **Christiansen filter**, named after Christian Christiansen.[28] It is based on the scattering of light and the lack thereof in the passband. The filter is a cell with particles suspended in a liquid. At most wavelengths, the particles scatter the light, but at the wavelength where the refractive indices of the particles and the liquid are equal, there is no scatter; the cell transmits. This is a rather cumbersome device and has given way to modern ones such as interference filters.

3.9 Lasers





Lasers—now an accepted English word but once the acronym for **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation—were invented in 1962 by

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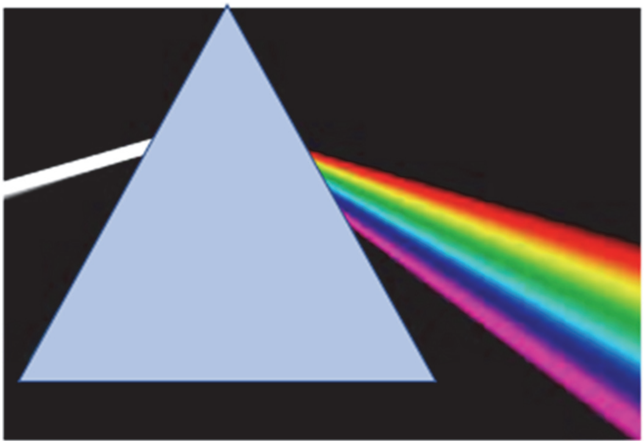
[27] Filter Design Software | *Nuts and Volts Magazine*, https://www.nutsvolts.com/magazine/article/filter-design-software.

[28] Christiansen, C. "Untersuchungen über die optischen Eigenschaften von fein verteilten Körpern," *Ann. Phys. Chem.* **23**, 298 (1884); **24**, 439 (1885).

calcite material splits the incoming beam into two with opposite polarizations. The parallel component is totally internally reflected at the interface because its refractive index is high enough. The perpendicular component passes through unaffected since its refractive index is low enough.

Circular polarizers turn unpolarized light or linearly polarized light into circularly polarized light, either clockwise or counterclockwise (viewed as it approaches). The secret of their operation is the quarter wave plate. A quarter wave plate is a birefringent material of a thickness such that the slower light is retarded by a quarter of a wavelength with respect to the faster polarization of opposite orientation. If they are adjusted to be of equal intensity, they will combine to give circular polarization.

3.13 Prisms



Prisms are of two major types: dispersive and non-dispersive. Polarizing prisms, which are a class of their own, are described in Section 3.12.

Dispersive prisms are used in spectrometers, multispectral imagers, projectors, television sets, and more. In every such case, they are used to disperse a spectrum, i.e., to spread the colors over space. The critical characteristic for a dispersive prism is its spectral resolving power, $\lambda/\Delta\lambda$. It is a measure of how well the prism spreads the light over space. The formula looks like it is upside down, but in this form, bigger is better. For a prism, it is the base length times the total refractive index change in the spectral band divided by that total spectral bandwidth. We might write that as $b\ \Delta n/\Delta\lambda$. It makes sense: spread the colors as much as you can with the total change in the refractive index Δn, and do it on a linear basis with a wider prism of base b. Then normalize with spectral spread $\Delta\lambda$.

Chapter 4

Optical Instruments

This chapter includes more than sixty different optical instruments. They range from the very simple magnifying glass, which is just a lens, to ICBM detectors, which include telescopes, detector arrays, and electronics. They may have many moving parts, such as interferometers, or no moving parts, such as windows. The word "instrument" has several definitions and connotations, but I like the most general one for this chapter: "a means whereby something is achieved, performed, or furthered."[1] One would not normally think of a window as an instrument, but it sure does achieve keeping the heat out and letting the light in.

This chapter should be read a little at a time. Choose whichever application intrigues you and go there. The sections are arranged alphabetically and are independent but may depend on the material in chapter 1. There are a few cross-references, but that should not be a problem.

Enjoy the scope of endeavors the optical instruments support. Enjoy the fact that we have a good defense against ICBM attacks. Anticipate the advent of holographic TV, autonomous cars, better traffic control, better cancer detection, and maybe a peaceful world.

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[1] Merriam Webster, Merriam-Webster.com.

Figure 4.3.8 Visible nighttime view.

Figure 4.3.9 Infrared nighttime view.

4.4 Autonomous Vehicles

They are coming, and they are here. Optics is a large part of what makes autonomous vehicles autonomous. It includes GPS, lidar, cameras, and computers.

The **GPS system** is used to locate the vehicle. GPS is only marginally optical. It uses three or four of the 24–30 GPS satellites for triangulation (quadrangulation?). The lengths to the ground vehicle from the satellite are determined by the time it takes for the round trip of light. The onboard computer does the calculation and sends the information to the vehicle by radio signals. It keeps tabs on time with atomic clocks, and it corrects time variations due to relativistic effects. Time increases in the reduced gravity field of the orbital altitude, and it decreases with orbital speed. The uncertainty of this location has been improving with time from about 3 meters to 30 centimeters, about one foot.[10]

A **lidar** on top of the car spins a full 360 degrees to sense and range all objects forward, to the sides, and even the rear to see if something might be

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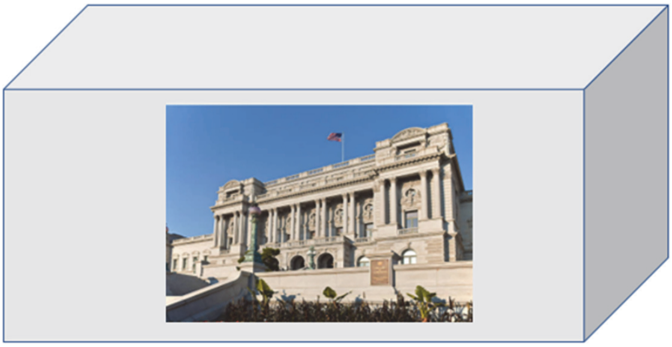
[10] Wikipedia. GNSS (GPS) accuracy explained Jupiter Systems https://junipersys.com/support/article/6614.

4.18 Holography



Holos and *gramma*, Greek for "whole writing," are the origins of the words "hologram" and "holography." It is a way of presenting true three-dimensional images.

The idea was conceived by Dennis Gabor in 1948.[31]

The first realization was by Emmett Leith and Juris Upatnieks at my old stomping grounds, the Willow Run Laboratories of the University of Michigan, in 1962.[32] That is a bit like Maiman, who did what Townes and Shawlow predicted theoretically (see Section 3.9). Emmett did what Gabor predicted theoretically.

As an interesting aside, the Ann Arbor papers completely missed the significance of holography. The headlines and articles were all about how Emmett had accomplished imaging **without lenses**, not that they were 3D.[33] I guess that is not the first nor will it be the last time the media has gotten or will get it wrong.

The process is one of optical interference. A laser beam is shone onto the desired scene through a beam splitter. One portion of the beam is used for a reference. The laser light reflected from the scene is combined with the laser light from that reference. It is recorded as an interference pattern and called a hologram. Recall that the interference of two light fields is three-dimensional. Therefore, a hologram is a recording of a three-dimensional interference pattern.

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[31] Gabor, D. "A new microscopic principle," *Nature* **161**, 777 (1948).

[32] Leith, E. and Upatnieks, J. "Reconstructed wavefronts and communication theory," *JOSA* **52**, 1123 (1962).

[33] My observations—I lived there then.

The process is simple but very technical and precise. First, the doctor must obtain a precise topographic map of the cornea to determine what to correct. This is done with a pachymeter, which is either optical or sonic. It uses either an optical pulse technique, such as lidar, or sound pulses, such as sonar.

The actual corneal reshaping process starts with generating a hole in the outer layer of the cornea, the epithelium, with either a scalpel or an excimer laser.[57] Then the shaping begins. Material is removed by short pulses from that excimer (excited dimer) laser at 193 nm. It removes the tissue without generating any heat or cutting, removing about ten micrometers at a time, by giving the molecules enough energy to jump out of their skin. (The photon energy exceeds the molecular binding energy.) The cornea is about 500 μm thick; these are small changes, about 2%.

There is a satisfaction rate of more than 90%. The reshaping process is quick and painless. The patients sit in a typical medical chair with a head restraint for about thirty minutes, and they then get up and walk out of the office. They can then sing, ♬ “I Can See Clearly Now . . . ” ♬

4.24 LIDAR

Lidar stands for “light detection and ranging.” It is analogous to radar, which stands for “radio detection and ranging.” It might also be called “laser detection and ranging,” because all of them use a laser as a source. It is the same technology applied in two different parts of the electromagnetic spectrum. There are two different types of lidar ranging: Doppler and time of flight.

The Doppler version makes use of the shift in frequency caused by the (in-line) motion of the target, also called the red shift (Section 1.10). For many applications, that frequency shift is too small to be detected. The shift is proportional to the ratio of the speed of the object to the speed of light. For a car traveling at 100 mph, that ratio is approximately 10^{-6}, one part in a million. That frequency shift is too small for automobile applications, but it is very useful in a variety of astronomic and atmospheric investigations.

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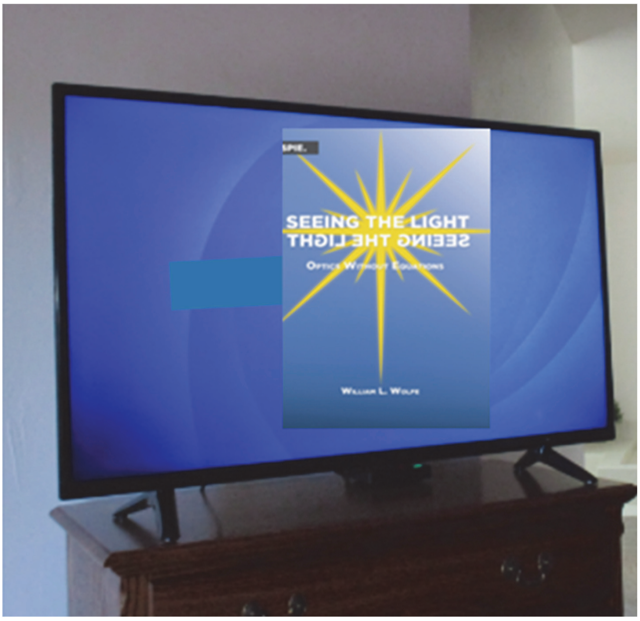
[57] I participated in this laser surgery performed by Robert Snyder, MD, at the University of Arizona Ophthalmology Department, and observed what he did.

4.55 Television Sets



I have lived through the entire age of television, from the 12-inch black-and-white sets of the 1940s to the Jumbotrons of today. Today is better.

Those old sets used cathode ray tubes (CRTs). For nostalgia's sake, I will review the concepts of their operation before a discussion of the versions of today. There are still some CRT sets around.

The **pickup tube** or **video recorder** unit in the broadcast station of those old devices started with an electron gun, which I have shown on the right of Figure 4.55.1. It has a negative applied voltage. The grid to the left of it in blue is positive and attracts the electrons (in the z direction, to the left). The electromagnetic deflection plates direct the electron current in the x and y directions (up and down, in and out). The optical system focuses an image on the grid that generates electrons by energy conversion in a photelectric material, one that exchanges electrons for photons. The number of electrons in each spot dictates the final current by repelling the electrons from the gun different amounts and thereby decreasing the current.

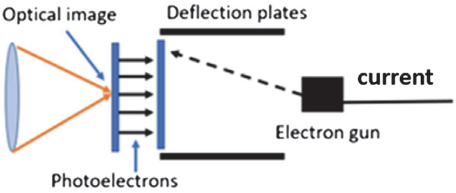


Figure 4.55.1 CRT schematic.

Chapter 5

Optical Experiments

This chapter is about several significant optical experiments that helped explain our universe and the nature of light. Galileo observed the phases of Venus to establish the Copernican concept of a heliocentric universe, or at least the solar system. John Mather carried out the COBE-DIRBE experiment using the FIRAS instrument to confirm the "big bang" theory of the origin of the universe. Newton used a prism to show us that white light consists of a spectrum of colors. Young, Arago, and Fizeau collectively proved that light was a wave motion and not corpuscular. Lummer, Kurlbaum and others carried out careful experiments on blackbodies that allowed Planck to quantize emissions and start quantum mechanics. Einstein interpreted the photoelectric experiments of Heinrich Hertz to show that light was also particles, later named photons. Michelson and Morley carried out a test to establish the luminiferous ether and proved the opposite. It was one of the events that lead to relativity. The eclipse experiment headed by Arthur Eddington was one of several experiments that established the general theory of relativity.

The timeline of the epochal events is unusual. Two of them happened in the 1600s. Then nothing of import occurred until the 1800s and 1900s, when there was a flurry of activity. Perhaps it took two centuries of renaissance to get there. Finally, in the modern age when we could launch satellites, the experiment to confirm the big bang theory of the origin of the universe was performed.

5.4 Young's Double-Slit Experiment

This experiment was one of the turning points in the understanding of light (which is still not yet fully understood). The prevailing concept at the time was that light consisted of corpuscles. This was due to the famous Isaac Newton, who believed that they were small particles and had many others convinced. But there were some—including Huygens, Fresnel, and Young—who believed that light consisted of waves. This was one of the three experiments that showed light to be waves.

Thomas Young was a medical student at Göttingen University, but he was a very inquisitive genius. He studied optics, Egyptology, and other sciences. The presentation of the results of his double-slit experiment was on November 24, 1803 before the Royal Society of London. The essence of the experiment is to divide a wave into two parts and then combine them to show that the parts interfere. The irony is that he did not use slits at all. Young's double-slit experiment was done without slits!

Young performed his experiment in much the same way that Newton showed that white light consisted of colors. He made a small hole in a window shade and directed the beam of light that came through it to a small card.[7] He held the card edgewise to the beam, thereby splitting it into two parts. The interference pattern appeared on the opposite wall. The experiment was later repeated with real slits.

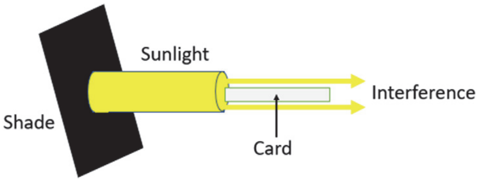


Figure 5.4.1 Young's arrangement.

It is easier to understand what he did by reference to the real double-slit arrangement. In his day, there were no lasers. He needed a single source so that all the waves would be emitted in phase. He did this with a single slit. We can imagine that source on the left and an optical system to generate plane waves. They are incident on the double slit. Waves emanate from the two slits shown as circular crests that overlap, but are really spheres. Where they overlap, there is constructive interference, as diagrammed in Figure 5.4.2. The red line shows one locus of constructive interference. There are others where the crests of the waves coincide.

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[7] Young, T. "Experimental demonstration of the general law of the interference of light," *Philo. Trans. Royal Soc. London* **94** (1804); Shamos, M., ed., *Great Experiments in Physics,* Holt Reinhart (1959); Young, T. *A Course of Lectures on Natural Philosophy and the Mechanical Arts*, Joseph Johnson (1807).

5.7 Michelson Morley Experiment

In the late 1800s, little was known about the nature of light. The wave theory had supplanted corpuscles, but it was not yet understood that light was electromagnetic radiation. Hertz had not done his experiment, and Maxwell was diligently working on his famous results. It was not yet understood how light (electromagnetic) waves propagated.[9]

Ocean waves travel in water. Sound waves move in air. The propagation is mechanical, from atom to atom. "There must be some sort of material in which light waves propagate;" was the prevailing thought at the time. The material proposed was the **luminiferous ether** or the "light-bearing upper air." It had to be more rigid than steel to support the high-frequency light waves but also massless and with no viscosity so that planets could pass through it unhindered. It had to exist in vacuum and throughout all space. That means as we spun around the sun on a daily basis, the stationary ether would seem to be a wind.

It was also a figment of the imagination.

Albert Abraham Michelson and Edwin Williams Morley set out to prove its existence.[10] They figured they would show that there was an ether wind by making measurements in two perpendicular directions—north and south versus east and west. Light that travels with the flow of the ether takes longer to go a given distance than light traveling perpendicular to the same flow. This can be measured by an interference effect in the Michelson interferometer (see Section 4.21). The Earth spins through the ether as sketched in Figure 5.7.1. It creates a wind by that relative motion, as shown schematically in Figure 5.7.2. This is analogous to the wind dogs love as you drive through still air.

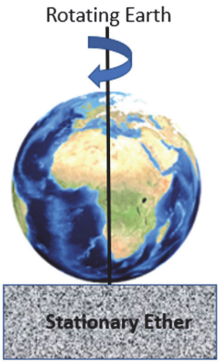

Figure 5.7.1 Spinning Earth.

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[9] Wolfe, W. *Rays Waves and Photons*, IOP Publishing (2020).

[10] Michelson, A. and Morley, E. "On the relative motion of the Earth and the luminiferous ether," *Am. J. Sci.* **34**, 203 (1887).

The gravitational red shift is related to the Doppler shift only in the sense that they are both shifts in the frequency of light. The Doppler red shift is caused by the fact that the source and receiver are moving apart. The gravitational red shift is caused by the photon expending energy as it moves against a gravitational attraction. The energy of a photon is the constant h times the frequency. The constant does not change; energy was lost. Therefore, the frequency is reduced, and the wavelength gets longer—to the red. The effect has been measured with stars and on Earth.[20]

One experiment that is not widely reported was carried out by one of my colleagues at Washington State University. For reasons that are a bit beyond me, he was a collector of atomic clocks. He took three of them with him when he camped high up on Mount Washington, while he left the others at home. He compared them at the end of the weekend. Sure enough, the ones at home were measurably slower than those he took camping The difference in time, based on the difference in altitude that resulted in the difference in gravity, could only be measured by atomic clocks since it was so small. Nanoseconds again!

5.11 The COBE-DIRBE Experiment

This experiment was done to test the “big bang” theory of the origin of the universe. The basic idea is that our universe began with a “big bang” that happened 3.8 billion years ago. It was a giant ball of intense plasma at an incredibly high temperature. A temperature so high that temperature has no meaning. Through the years, it cooled until now the outer reaches of our universe are at a temperature of about 3 degrees Kelvin above zero (2.72548 ± 0.00057 K, to be exact). Those outer reaches where there are no stars or planets (or anything) should radiate as a blackbody at that temperature. This phenomenon is called the cosmic background radiation.

The Far-Infrared Absolute Spectrophotometer (FIRAS) was the instrument John Mather used to perform this experiment. It measured the spectrum of that primordial radiation and found it to match that of a blackbody at 2.725 K. Mather used a Michelson interferometer spectrometer that operated in the far infrared at a temperature of 1.5 K to keep its self-radiation from interfering with the measurements.

The Michelson interferometer spectrometer is described in Section 4.47. This one used wire grids as polarizing beam splitters. The measured

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[20] Hetherington, N. “Sirius B and the gravitational redshift - an historical review,” *Quarterly J. Royal Astro. Soc.* **211**, 246 (1980).