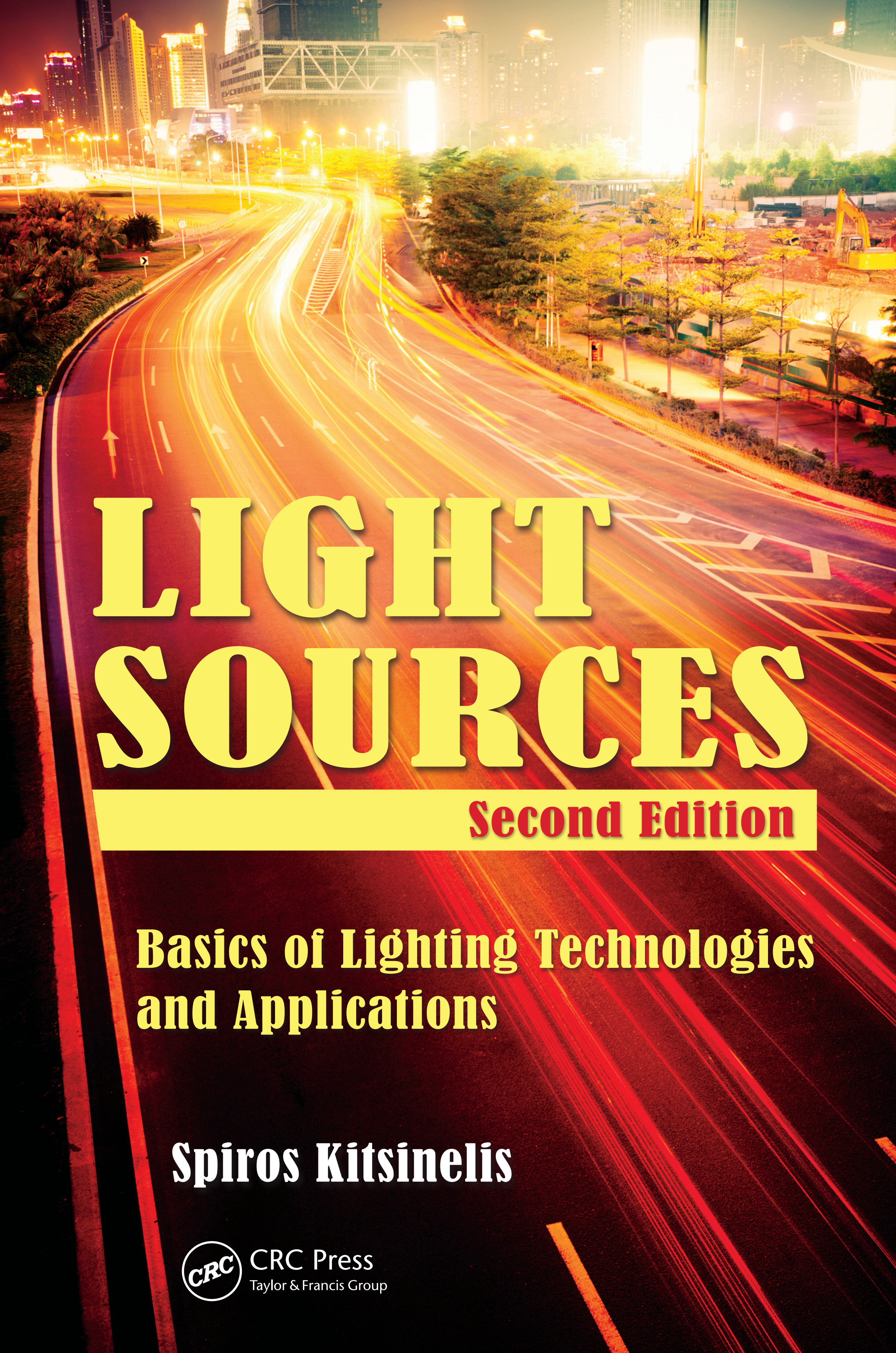

LIGHT SOURCES

Second Edition

Basics of Lighting Technologies and Applications

Spiros Kitsinelis

CRC Press
Taylor & Francis Group

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Dedicated to my son Christos…the light of my life!

Contents

Prologue

The spread of electricity and the development of power grids that began with Thomas Edison changed the way we illuminate our lives and created a new industry. The present book, just like its first edition, provides an overview of the three main technologies that gave birth to the numerous families of products one can find in the market today. Electrical *incandescence*, electrical *gas discharges*, and semiconductor *light-emitting diodes* are those three dominant technologies that have lighted our world for more than a century.

This second edition not only provides updates on the scientific and technological developments of existing and new light sources but also expands on the topic of applications. Different lamp technologies are characterized based on a large number of parameters that need to be taken into account before making a choice; but in this book, the selections and proposals for various applications are based mainly on the "quality" of light, which basically means the *color/wavelength* of the light, the *color rendering index* of the source, and in the case of white light—the *color temperature*. In some cases, other parameters such as the luminous flux or the lifetime may play a role.

This book will assist lighting engineers design the most appropriate environments for people with various needs and professions. Health professionals will be able to create the appropriate visual environment for people with different medical conditions, thus improving the quality of life for many groups of citizens. The book will also serve as a guide for authorities who have to choose the correct technology for cost-effective lighting schemes in order to increase the security and aesthetics of communities. Finally, it will help the ordinary citizen decide which technology will suit him or her the best at home or at work.

Other Sources

This book is an overview of all the main technologies and important families of light sources that have dominated the market and our lives since the end of the 19th century. It is not, however, an exhaustive list of all the available commercial products. There is no point in trying to keep up with all the special characteristics of new products, which change rapidly, and this type of update would be better served by the catalogs of all the major companies.

The photographic material in this book comes from three main sources:

- The author's own collection
- The Museum of Electric Lamp Technology (J.D. Hooker, http://www.lamptech.co.uk)
- Wikimedia Commons (http://commons.wikimedia.org)

The reader will find references at the end of the chapters regarding specific research results, but the general information presented throughout this book is based on the following two important sources:

- *Lamps and Lighting*, 4th Edition, by J.R. Coaton and A.M. Marsden, 1996, London: Routledge/Taylor & Francis Group
- *Electric Discharge Lamps*, by John Waymouth, 1971, Cambridge: MIT Press

More information and publications on lighting design and standards can be acquired from a number of professional organizations such as:

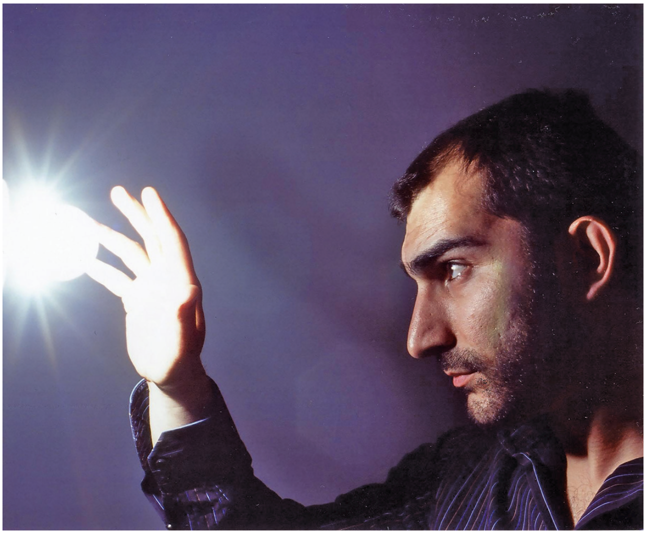
The *International Commission on Illumination* (CIE), which is an international authority and standard defining organization on color and lighting. CIE publishes widely used standard metrics such as various CIE color spaces and the color rendering index (http://cie.co.at).

The *Illuminating Engineering Society of North America* (IESNA) publishes lighting guidelines, standards, and handbooks (http://www.ies.org).

The *International Association of Lighting Designers* (IALD) is an organization that focuses on the advancement of lighting design education and the recognition of independent professional lighting designers (http://www.iald.org).

The *Professional Lighting Designers Association* (PLDA) is an organization focused on the promotion of the profession of architectural lighting design (www.pld-c.com).

About the Author



Spiros Kitsinelis, Ph.D., is a researcher whose focus is on the development of novel and energy efficient light sources and on the communication of this science to a broader audience. He earned his master's and Ph.D. degrees in chemistry from the University of Sheffield in England for his research and development of pulse-operated low-pressure plasma light sources in the High Temperature Science Laboratories. He continued his research as a postdoctoral fellow at Ehime University in Japan in the Department of Electrical and Electronic Engineering. Dr. Kitsinelis held the position of project leader at Philips Lighting Central Development Lighting in the Netherlands, and continued his research and development of the next generation of plasma light sources for the Physics

Department of the National Technical University of Athens, Greece. After a respite from research when he served as a chemical engineer for the armed forces, he acted as the National Contact Point for Energy at the National Documentation Centre of the National Research Foundation of Greece; set up the electronic periodical *Science and Technology of Light Sources* (*SATeLightS)*; and later worked as a researcher at Paul Sabatier University in Toulouse, France.

Dr. Kitsinelis is the author of a number of scientific publications, has attended many international conferences, and is the cocreator of a number of patents in the field of light sources. His science communication activities include books, television and radio shows, science film festivals, and articles in popular magazines. His latest academic position was that of associate professor at Ehime University in Japan. His personal Web site contains more details at: www.the-nightlab.com.

Dr. Kitsinelis has previously published two books with CRC Press/Taylor & Francis: *Light Sources: Technologies and Applications,* First Edition (2010), and *The Right Light: Matching Technologies to Needs and Applications* (2012).

Acknowledgments

For this second edition I would like to thank my editor Luna Han at CRC Press/Taylor & Francis for her efforts; my Ehime University colleague, Professor Masafumi Jinno, for his guidance in all professional matters; and finally the readers of the first edition of *Light Sources* who supported the publication.

Introduction

Humanity has to deal with two main issues regarding energy. The first is the availability of nonsustainable energy sources and whether the global demand for energy can be met. This is due to energy source depletion in certain parts of the world or due to geopolitical factors, and in any case, the impact to the global economy is substantial. The second issue is one that deals with the environmental changes of the planet and the impact these changes have on our lives. The burning of fossil fuels as the most common energy generation mechanism results in the formation and emission of carbon dioxide as a byproduct, which is one of the gases responsible for the greenhouse effect.

Considering that humans are using about a fifth of the world's generated electric energy for lighting applications [1,2], it is easy to appreciate the importance of light source technologies both from an economic perspective and from an environmental standpoint. Light sources and lighting not only represent an economic market of billions of dollars but the consumption of energy for lighting is responsible for the generation of millions of tons of CO_2 gas annually.

Furthermore, light is vital and light sources play an indispensable role in daily life. The quality of life, including aspects such as health and urban security related to traffic and crime prevention, depend on light and its quality. Of course, the use of light sources is not limited to general lighting, but also to a range of other applications that require emissions in the ultraviolet and infrared part of the electromagnetic spectrum, such as sterilization, health science, aesthetic medicine, art conservation, food processing, and sterilization of hospitals or water, to name a few.

Efforts to create light at will, as well as to understand its nature, started thousands of years ago with the use of fire. Over time, the burning of wood was replaced by the burning of oil and later, in the 18th century, by the burning of gas. The harnessing of electricity and its use brought about a revolution not only in the way we live our lives but also in the way we light our lives. Electric lighting technologies have been with us since the middle of the 19th century and have been evolving ever since. The first technology, incandescence of a filament, was due to the efforts of people such as Heinrich Gobel in the middle of the 19th century, and Joseph Swan and Thomas Edison a few years later. The second technology, electrical discharge through gas, became widespread in the beginning of the 19th century thanks to Humphry Davy. The third technology, the use of diodes resulting from developments in the semiconductor field, was born much later in the middle of the 20th century, once again revolutionizing the field of lighting.

When Isaac Newton analyzed white light into its constituent colors in the middle of the 17th century, explaining the formation of rainbows, he did not discount the magic of this phenomenon but opened the door to another magical world that had to do with the nature of light. Even though since the time of the ancient Greek philosophers, questions regarding the way the human eye functions and the nature of light continue to tantalize scientists. Today, after centuries of experiments and scientific disputes, certain ideas and theories have been proven and become universally accepted. Some of the basic properties of light will be discussed in Chapter 1.

References

1. European Commission, Directorate-General for Energy and Transport (2007). EU energy and transport in figures. Statistical Pocketbook 2007/2008. http//ec.europa.eu/dgs/energy_transport/figures/pocketbook/doc/ 2007/2007_pocketbook_all_en.pdf.
2. International Energy Agency (2006). *Light's Labour's Lost: Policies for Energy-Efficient Lighting*. http://www.iea.org/publications/freepublications/publication/light2006.pdf.

1 Basic Principles of Light and Vision

1.1 Properties of Light

It is imperative to begin by defining several terms used throughout the book that will help the reader understand the properties of lamp technologies available and how light affects an individual. In addition to the introduction of the basic principles of light and vision, the reader may also refer to the Glossary where definitions of the various terms are provided.

As seen in Figure 1.1, visible light is just a small part of the electromagnetic spectrum to which the human eye is sensitive and it includes waves with lengths from around 380 nanometers (10^{-9} m) to about 780 nanometers. On the lower energy side, the spectrum starts with radio waves used to transfer images and sound (like radio and television) and continues to microwaves, used in devices such as radar and ovens. Further down the spectrum are infrared waves, which are perceived as heat. On the higher-energy side of the visible spectrum with shorter wavelengths is ultraviolet radiation. Thus, X-rays are used in medicine for bone outlining; next are gamma rays and finally cosmic rays. Different regions of the electromagnetic spectrum are also presented in Appendix A.

Since the mid-17th century scientists have been divided regarding the nature of light. One side, which included Isaac Newton, believed in the corpuscular property of light and spoke of the effects such as reflection and shadows to support their views. The other side, which was supported by Christian Huygens, believed in the wave properties of light as shown by phenomena such as diffraction. In the early 20th century, the conflict on the nature of light was resolved when scientists and, in particular, Albert Einstein and Louis de Broglie, provided a new picture of quantum physics by showing the duality of matter and energy at the atomic level.

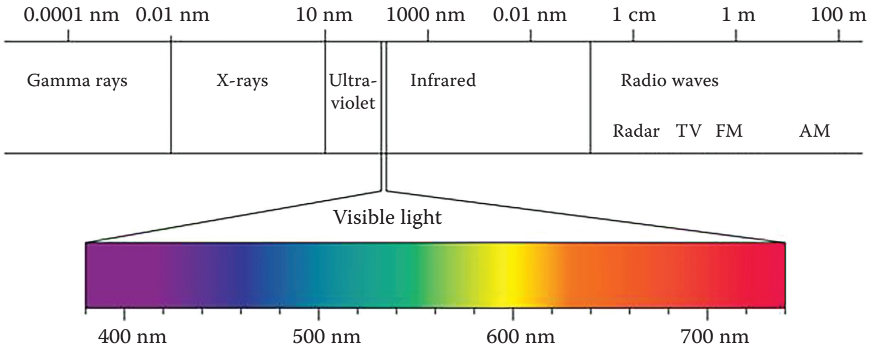


Figure 1.1. Visible light is part of the electromagnetic spectrum and consists of a series of waves with lengths from 380 to 780 nanometers that humans perceive as color.

A series of experiments showed that photons act like particles as demonstrated by the photoelectric effect and Compton scattering but also act as waves. Today, this property continues to be one of the most interesting and bizarre aspects of the natural world.

When discussing the wave property of photons, we talk about electromagnetic waves, which are characterized by intensity, wavelength, and polarization. Electromagnetic waves are transverse waves where the oscillation is perpendicular to the direction of travel, as we know from James Maxwell's equations and the experiments of Heinrich Hertz. Accordingly, an electric field changing over time creates a magnetic field and vice versa. These two fields oscillate perpendicular to each other and perpendicular to the direction of the motion of the wave (Figure 1.2).

Regardless of the wavelength, waves travel at the same speed in a vacuum (299.792458 km/sec) and the electromagnetic spectrum extends from radio waves with wavelengths of up to several kilometers to cosmic rays with wavelengths of

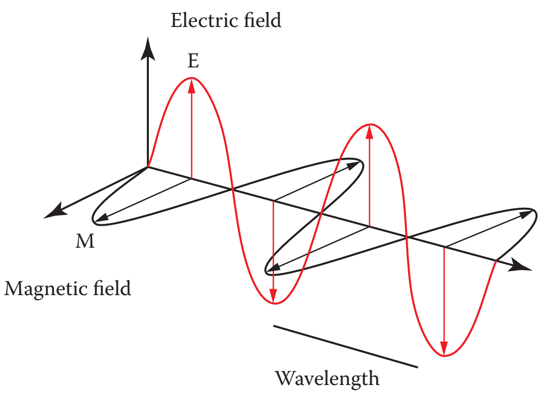


Figure 1.2. Electromagnetic wave propagation.

a few Angstrom (10^{-10} m). The relationship between energy and the wavelength or frequency is given by the formula

$$E = h \cdot v = (h \cdot c)/\lambda$$

where
E = energy (joule)
v = frequency (Hz)
h = Planck constant (6.626 × 10–34 J·sec)
c = speed of light in vacuum (2.998×10^8 m/sec)
λ = wavelength (m)

Spectrometers analyze light and other radiation by making use of the wave properties of light such as refraction or the interference that comes from diffraction.

The principle of refraction is a change of direction following a change in the speed of the waves that happens when a wave passes from one medium to another with a different optical density, which is called a *different refractive index*. Figure 1.3 depicts this change of direction when the medium changes.

The angle of incidence and the angle of refraction are related to the refractive indices of the media and this relation is described by Snell's law

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

where n is the refractive index of each medium and $\sin\theta$ is the sine of each angle (for example, air has a refractive index of 1.0003; for water it is 1.33; and for glass it is 1.5–1.9, depending on the type of glass).

If the angle of incidence exceeds a specific value, then the wave is totally reflected without refraction taking place. This effect, which can be observed only

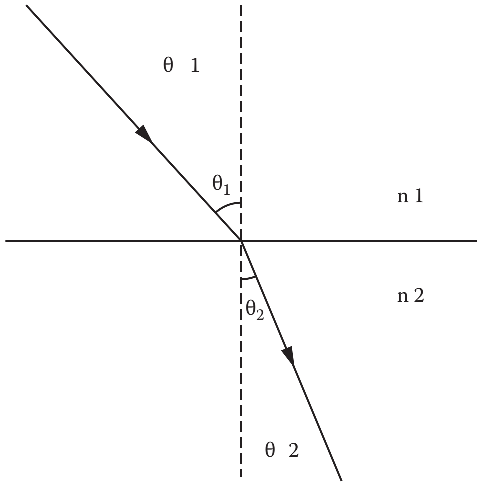


Figure 1.3. Wave refraction.

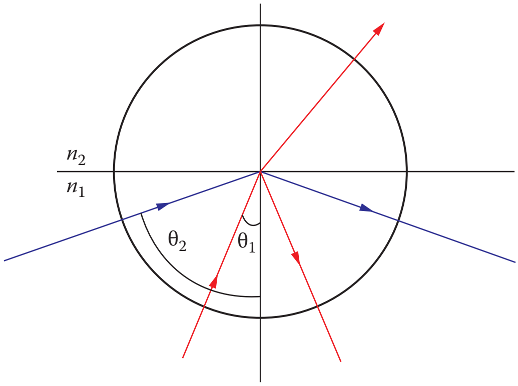


Figure 1.4. Total internal reflection.

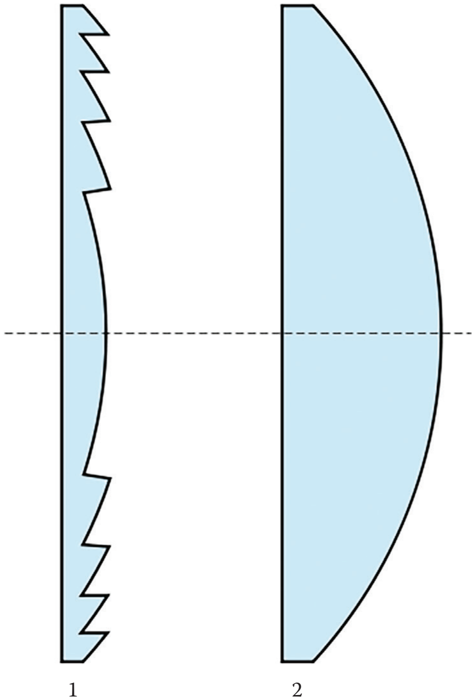


Figure 1.5. Fresnel lens (1) and conventional lens (2).

for waves traveling from a medium of a higher refractive index to a medium of lower refractive index (glass to air, not vice versa), is known as *total internal reflection* and it is the principle upon which optical fibers work (Figure 1.4).

Refraction is behind the optical properties of lenses. The Fresnel design (Figure 1.5) allows for the construction of large lenses by reducing the volume and weight that is required for the construction of conventional lenses. Refraction is

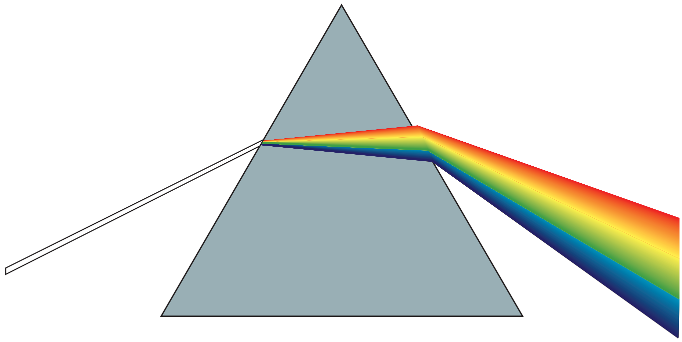


Figure 1.6. Prism diffraction analyzing white light to its constituent colors.

also responsible for the effect of the rainbow and the analysis of white light into its component colors through a prism. The different frequencies of different colors travel at different speeds when they enter a new medium leading to different directions for each wave of a different color. This phenomenon is also called *chromatic aberration* and can be seen in lenses of inferior quality, which means that the wavelength affects the refractive index of the medium. The color of the sky at sunset and changes in the color of the moon are the result of refraction where the Earth's atmosphere acts as the second optical medium. What is important to remember at this point is that—*shorter wavelengths are refracted to higher degrees than longer ones*—so, for example, blue is refracted more than red. Figure 1.6 demonstrates the refraction of white light through a prism. Each color is refracted to different degrees and therefore the waves move in a different direction resulting in the splitting of the different colors.

The other property of light is diffraction. When waves pass obstacles or find an opening of similar dimensions to their wavelengths they spread and interference occurs as shown in Figure 1.7. The interference results in new waves of intensity, which are equal to the sum of the intensities of the initial waves at each point. This relation could mean an increase or the zeroing of intensity at some point of the new wave. Figure 1.8 schematically shows the summation of wave amplitudes.

Figures 1.9 and 1.10 illustrate the effect of diffraction as seen in everyday life and how it is used for the development of scientific instruments.

Another interesting property that will be of value to our discussions is Rayleigh scattering, which is the elastic scattering of light by particles much smaller than the wavelength of the light, such as atoms or molecules. Rayleigh scattering can occur when light travels through transparent solids and liquids, but is most prominently seen in gases. Rayleigh scattering is inversely proportional to the fourth power of wavelength, so that shorter wavelength violet and blue light will scatter more than the longer wavelengths (yellow and, especially, red light). The Tyndall effect, also known as *Tyndall scattering*, is similar to Rayleigh scattering in that the intensity of the scattered light depends on the fourth power of the frequency, so blue light is scattered much more strongly than red light but refers to light scattering by particles in a colloid or particles in a fine suspension [1]. On larger

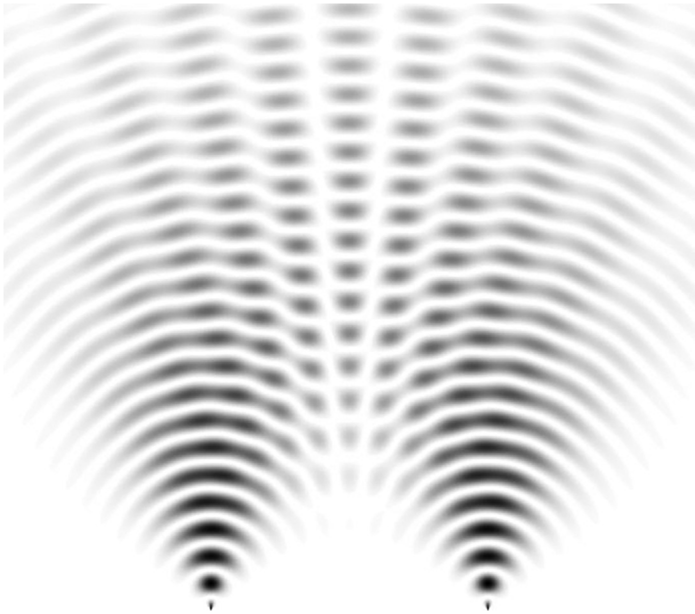


Figure 1.7. Wave interference.

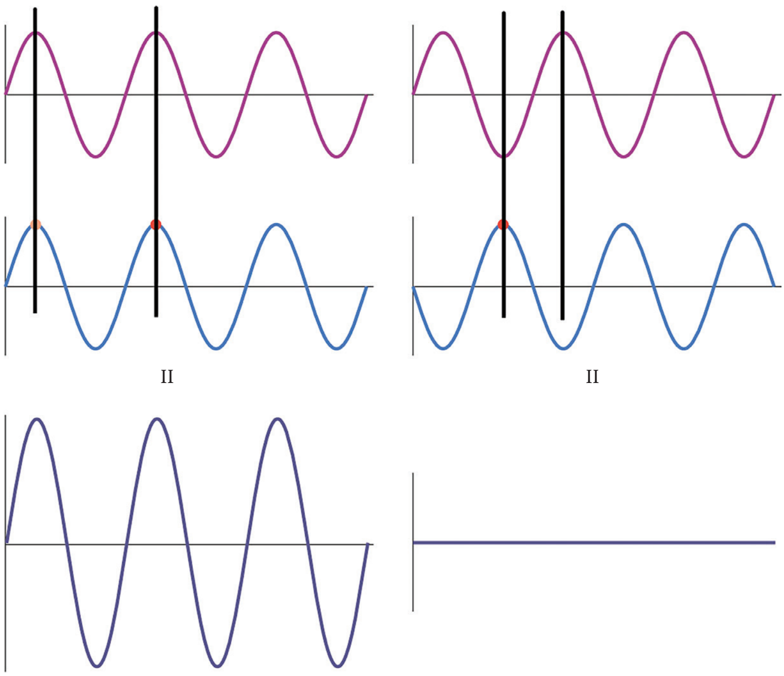


Figure 1.8. The wave interference can be constructive (left) or destructive (right) depending on the phase difference of the waves.

Figure 1.9. When light hits a surface with grooves such as that of a compact disk, diffraction occurs which leads to interference and the formation of colors.

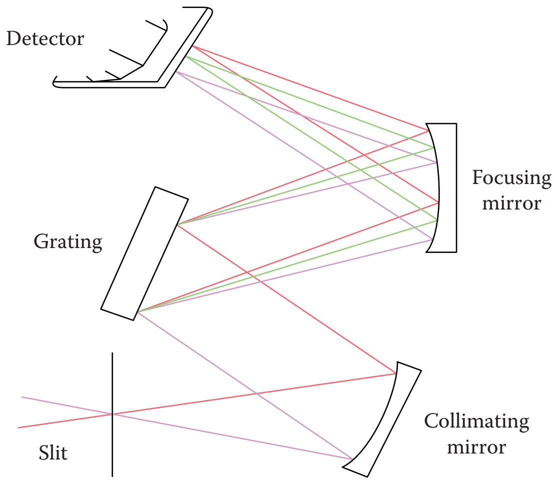


Figure 1.10. Spectrometers use the diffraction effect in order to analyze light into its component wavelengths.