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Light, Electromagnetic Spectrum

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Synonyms

Light – Light stimulus, Optical radiation, Electromagnetic radiation; Electromagnetic spectrum – Optical spectrum

Definitions

Light is so much a part of our everyday existence contributing to our quality of life, as well as a key enabler in photonics, solar power, and new lighting technologies, that the year 2015 has been declared by the UNESCO as the International Year of Light and Lighting Technologies.

Light has many different meanings depending upon the application.

When it is used to broadly describe *optical radiation*, it is defined as electromagnetic radiation with wavelengths between approximately 10 nm and 1 mm, i.e., a term that is used to describe the ultraviolet, visible, and infrared regions of the electromagnetic spectrum.

When it is used to describe a *light stimulus*, the International Lighting Vocabulary [1] gives the following two definitions: (1) It is a characteristic of all sensations and perceptions that is specific to vision, and (2) it is radiation that is considered from the point of view of its ability to excite the human visual system, i.e., it is limited to electromagnetic radiation with wavelengths in the visible spectral region between approximately 380 and 780 nm.

The term *light* is also sometimes used as a synonym for *electromagnetic radiation* which encompasses not only the ultraviolet, visible, and infrared range but also the X-ray and gamma-ray ranges and the radio range.

Electromagnetic radiation is the emission or transfer of energy in the form of electromagnetic waves and in the form of photons.

Photon is a quantum of electromagnetic radiation that is usually associated with radiation that is characterized by one wavelength or frequency (monochromatic radiation).

Electromagnetic wave is a transverse oscillation of inextricably linked electric and magnetic fields traveling through space; through empty space, it travels at the speed of light in vacuum; through other media, its speed is reduced by the value of the refractive index of the medium.

Electromagnetic spectrum is defined as the graphical representation of electromagnetic waves arranged according to their wavelength.

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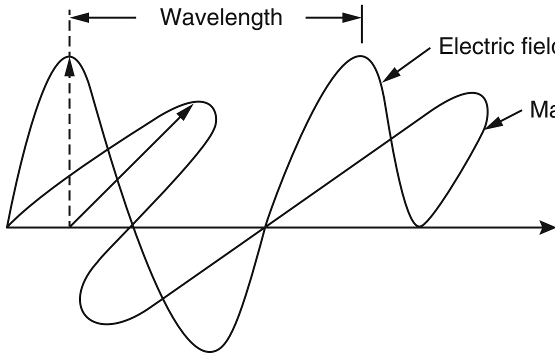


Light, Electromagnetic Spectrum, Fig. 1 Simplified picture of an electromagnetic wave. The oscillations are perpendicular to each other and to the direction of energy flow

Overview

Early Views of Light

The nature of light has intrigued philosophers and scientists for thousands of years. Because light travels in straight lines (*rectilinear propagation*), it was long believed that it was made of particles (corpuscles) that emanated from the source. However, some properties of light, such as the fussiness produced when light passes around obstacles or through openings (*diffraction*), needed a different model of light where it behaved like a type of wave or propagating disturbance. In the early 1700s, both the particle and wave models of light prevailed with Sir Isaac Newton being a staunch supporter of the particle theory and others, such as the Dutch physicist, Christiaan Huygens, being proponents of the wave theory [2]. But, in the early 1800s, when the English physician Thomas Young showed that light diffracted and interfered to produce fringes when it passed through a double slit, the wave model of light became the accepted theory. At the end of the nineteenth century, the particle theory of light was revived by Einstein, who used particle behavior and a new type of theory – quantum physics – to explain the photoelectric effect. It is now widely accepted that light exhibits all three of these behaviors: particle, wave, and quantum, which are used to explain all known properties of light [2].

The history of light has also included interesting debates on how it is propagated. Ancient astronomers thought that light traveled at infinite speed. The Greek philosopher Aristotle proposed that light propagated through a hypothetical substance, luminiferous ether or light-bearing ether, because it was believed that all types of waves required a medium for propagation such as sound waves in air and water waves in water. However, light is very different from other types of waves. In 1881, in one of the most famous experiments with light, Michelson and Morley tried to measure the rotational motion of the earth in this luminiferous ether [2]. However, they found that the light did not travel at different speeds for different paths. This failed experiment indirectly showed that light does not need a medium and can travel in free space (vacuum) and at constant speed. Michelson also carried out experiments to measure the speed of light by improving on Galileo's echo technique by replacing men carrying lanterns with a series of mirrors and a telescope. By adjusting the rotation speed of the mirrors, he could observe the light in the telescope, and from the rotation of the mirror and the known distance traveled by the light, he was able to determine the speed of light to about six significant figures [2]. Presently, the speed of light is the most accurately known fundamental constant of nature.

Description of Electromagnetic Radiation and Light

Electromagnetic radiation (emr) can also be described as the emission or transfer of energy from vibrating charged particles that creates a disturbance in the form of oscillating electric and magnetic fields (Fig. 1). The British physicist James Clerk Maxwell [3] was the first to discover that these electric and magnetic waves always occurred together, i.e., were coupled, giving rise to the name, *electromagnetic waves*. It was also found that the lines of force of these electric and magnetic waves were always perpendicular to each other and perpendicular to the direction of wave propagation, i.e., *transverse*, never longitudinal. This *transverse* nature of light gives rise to various phenomena associated with *polarization*.

Polarized electromagnetic radiation is defined as radiation whose electromagnetic field, which is transversal, is oriented in defined directions [1, 4] where this polarization can be linear, elliptic, or circular. Light is totally linearly polarized (or *plane polarized*) if the electric field vectors are all oriented in the same plane, parallel to a fixed direction which is referred to as the *polarization direction*. Light is *unpolarized* when its electric field vectors vibrate randomly in all directions; this can also be considered to be equal amounts of plane-polarized radiation whose vibration directions are perpendicular to each another. The *state of polarization* of the radiation (linear, circular, elliptic) is described by the phase relationship between these two orthogonal components. If this phase difference is zero or 180°, the radiation is *linearly polarized*; if the phase difference is 90° or 270° and both components have the same amplitude, the radiation is *circularly polarized*; and if the phase difference is not 0°,180°, 90°, or 270° and/or the amplitudes are different, the radiation is *elliptically polarized*.

Light is *partially polarized* if the electric vectors have a preferred direction. If the electric vector is polarized vertical to the plane of incidence, this is referred to as *s-polarized* (or TE), and if the electric vector is polarized parallel to the plane of incidence, this is referred to as *p-polarized* or (TM).

In addition to its state of polarization, these *electromagnetic waves* are characterized by several other measurable properties, such as the number of oscillations per second, the separation between successive peaks or troughs, and the size or amount of oscillations. These quantities are described by the frequency, v; wavelength, λ: and amplitude or intensity, I, respectively. The *intensity* describes the amount of energy flowing in the electromagnetic wave and is proportional to the square of the *amplitude*. It is also necessary to specify the *direction* that the wave is traveling, which is indicated in Fig. 1 by using an arrow. It can be seen that these waves crest up and down in a sinusoidal fashion, which is described as the *wave front* moving up and down. When more than one wave is traveling, it is important to describe how they differ in phase. Two waves are *in-phase*, if their crests coincide and their troughs coincide. Two waves are *out-of-phase*, if the crest of one wave coincides with the trough of the second wave and vice versa. A *plane wave* is a wave whose surfaces of constant phase are infinite parallel lines transverse to the direction of motion. If all of the waves vibrate in-phase, the emr is referred to as *coherent*. The laser is an example of a coherent light source. If there is no fixed phase pattern between the waves emitted by a light source, the emr is referred to as *incoherent*. Most ordinary light sources, such as an incandescent lamp, are examples of incoherent light sources.

Properties of Electromagnetic Waves

As mentioned above, generally a wave, such as a water wave, is a propagating disturbance of some equilibrium state in a continuous medium. However, no medium is required for propagation of electromagnetic waves. This property of electromagnetic waves makes them unique from other types of waves that can be considered mechanical in nature and was first demonstrated by Einstein in 1905. He also proposed the idea that light could behave both as a wave and as a particle in order to explain the spectral distribution of the radiation emitted from a hot (incandescing) object. This type of electromagnetic radiation is referred to as *blackbody radiation* (give link to encyclopedia article on blackbody radiation).

Electromagnetic waves of all wavelengths travel exactly at the same speed in vacuum. This fundamental constant of nature is known as the *speed of light in vacuum*, denoted by the symbol, c. It has a value of 299,792,458-metre per second.

Light, Electromagnetic Spectrum, Table 1 Regions of the electromagnetic spectrum

Wavelength range (nm)	Frequency range (s^{-1})	Description
<0.1 nm	10^{20}–10^{23}	Gamma rays
0.1–10 nm	10^{17}–10^{20}	X-rays
10–400 nm	10^{15}–10^{17}	Ultraviolet
400–700 nm	10^{14}–10^{15}	Visible
700 nm to 1 mm	10^{11}–10^{14}	Infrared
1 mm to 1 cm	10^{10}–10^{11}	Microwaves
1 cm to 100 km	10^{3}–10^{10}	Radio waves
100–1,000 km	10^{2}–10^{3}	Audio frequency

The frequency, v, is related to wavelength, λ, by $v = c\lambda^{-1}$. Waves are also sometimes described by their *wave number*, σ, which is the inverse of wavelength, defined by $\sigma = \lambda^{-1}$.

When an electromagnetic wave travels through other media such as air, glass, or water, its frequency remains constant, but its wavelength and speed are both reduced by a factor, n, the *refractive index* of the material. For commonly used optical glasses, the value of n ranges from 1.52 to 1.72 and is a function of frequency. For standard air, n has a value of 1.00028 [5] and can be ignored for most practical applications.

The behavior of electromagnetic waves at the boundary from one medium to another giving rise to reflection, transmission, and refraction phenomena is described by a set of wave equations known as *Maxwell's equations* [6].

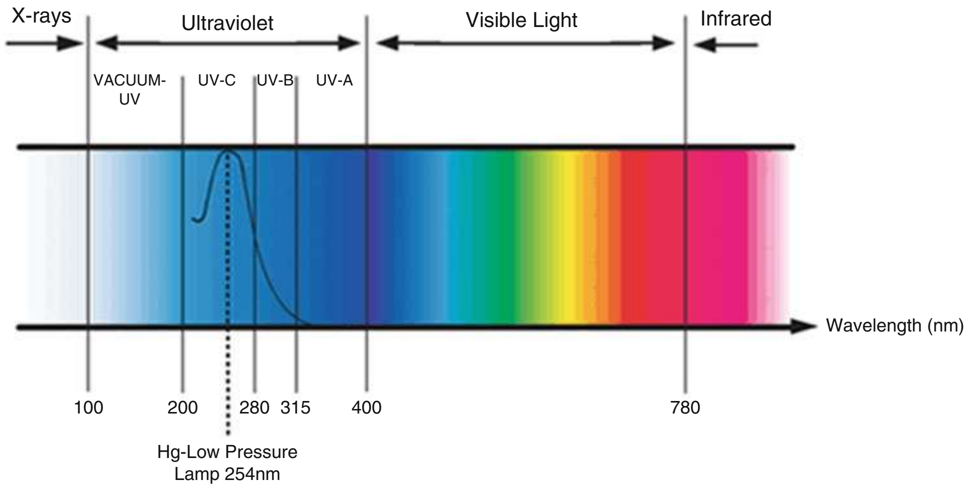
These four equations have become the fundamental laws in electromagnetics connecting the principles of electricity and magnetism. Solving these equations reveals the wave equation and the form of the electromagnetic waves. The Maxwell's equations are not given here because this is outside the scope of this entry; the interested reader can find a good description in the following references [2, 6].

The smallest unit or quantity of electromagnetic radiation is called a *photon*. The energy of a photon is given by $E = hv$ where h is Planck's constant (6.62606×10^{-34} J s). Light can then be described as a stream of individual photons, each with a definite energy and that can interfere with each other like waves and diffract around corners [3]. The motion of these photons is controlled by these same set of Maxwell wave equations [2, 3].

The *electromagnetic spectrum* spans the total range of wavelengths of electromagnetic radiation from the shortest to the longest wavelength that can be generated physically. This range of wavelengths spans practically from zero to near infinity and can be broadly divided into regions as shown in Table 1 [7], which includes radio waves, infrared, visible, ultraviolet, X-rays, and gamma rays. This division is not exact since there is a gradual transition from one region to the next, which is shown schematically in Fig. 2 where the visible and ultraviolet regions are highlighted. This classification of light into regions is also shown as a function of frequency. It is important to note that the only difference between electromagnetic radiations in all these regions is its wavelength (and frequency). It has different descriptions because of the relationship between its frequencies and those that are excited in the various materials that the electromagnetic radiation can interact with. For example, the visual receptors in the human eye are only sensitive to electromagnetic radiation in a very narrow frequency range from 10^{14} to 10^{15} s^{-1} (or 400–700 nm), whereas X-rays are used to excite features in the body that are of the size of an atom (0.1 nm). These different applications of emr are described in more detail below.

Interaction of Light with Matter

When light interacts with matter, different phenomena can occur depending upon the relationship of the wavelength (frequency) of the light



Light, Electromagnetic Spectrum, Fig. 2 The regions of the electromagnetic spectrum, highlighting the optical spectrum which includes the visible and ultraviolet regions.

with the physical size (resonant frequencies) of the interfering matter. This matter consists of atoms, ions, and molecules. As mentioned above, only light in the visible portion of the spectrum with frequencies from 10^{14} to 10^{15} s^{-1} can stimulate the visual receptors in the human eye. Light can also exhibit wave or particle properties depending upon this relationship between size (or frequency). For light waves that are closely spaced in relation to the spacing of the interfering matter, for example, a wave front passing through a slit or an opaque edge, secondary wave fronts are generated. These will interfere with the primary wave front, as well as with each other, and produce *diffraction* patterns. Since these secondary wave fronts were produced from the same primary wave, their phase will change in step. Thus, even for a normally incoherent light source, wave-like behavior such as *diffraction* and *interference* can be seen under certain conditions [8].

Many colorful effects are produced by this combination of light *diffraction* and *interference*. In nature, this can be seen, for example, in the beautiful array of colors displayed by mother of pearl (*opalescence*) or by thin film *iridescence* (add link to iridescence article). For light waves that are very small in relation to the interfering particles, such as the interaction of visible light with dust particles or gas molecules in the atmosphere, *Rayleigh scattering* occurs which produces the blue color of the sky (add link to Rayleigh and Mie scattering article).

However, when light interacts with objects that are large in relationship to their wavelength, such as a brick wall or pane of glass, the light behaves more like a ray (particle) and the laws of geometrical optics can be applied.

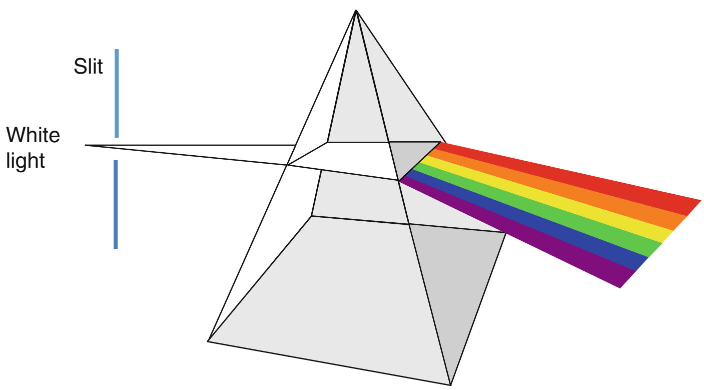
Depending upon the transparency or translucency of the material and its surface quality, the light will be reflected, refracted, transmitted, absorbed, or scattered. The type of light interaction that dominates depends upon the precise nature of the matter, e.g., for a smooth opaque colorless solid, specular (mirror-like reflection) will dominate, whereas for an opaque colored material, diffuse reflection or scattering will dominate. The selective modification of the energy distribution of the incident light by the diffusely reflecting material gives rise to different colors.

Light Intensity Distribution and Color

The different wavelengths in the visible spectrum can also directly stimulate different colors in the human visual system. This dependence of color on wavelength is shown in Table 2.

Light, Electromagnetic Spectrum, Table 2 Dependence of color on wavelength

Wavelength range (nm)	Color
400–430 nm	Violet
430–480 nm	Blue
480–560 nm	Green
560–590 nm	Yellow
590–620 nm	Orange
620–700 nm	Red



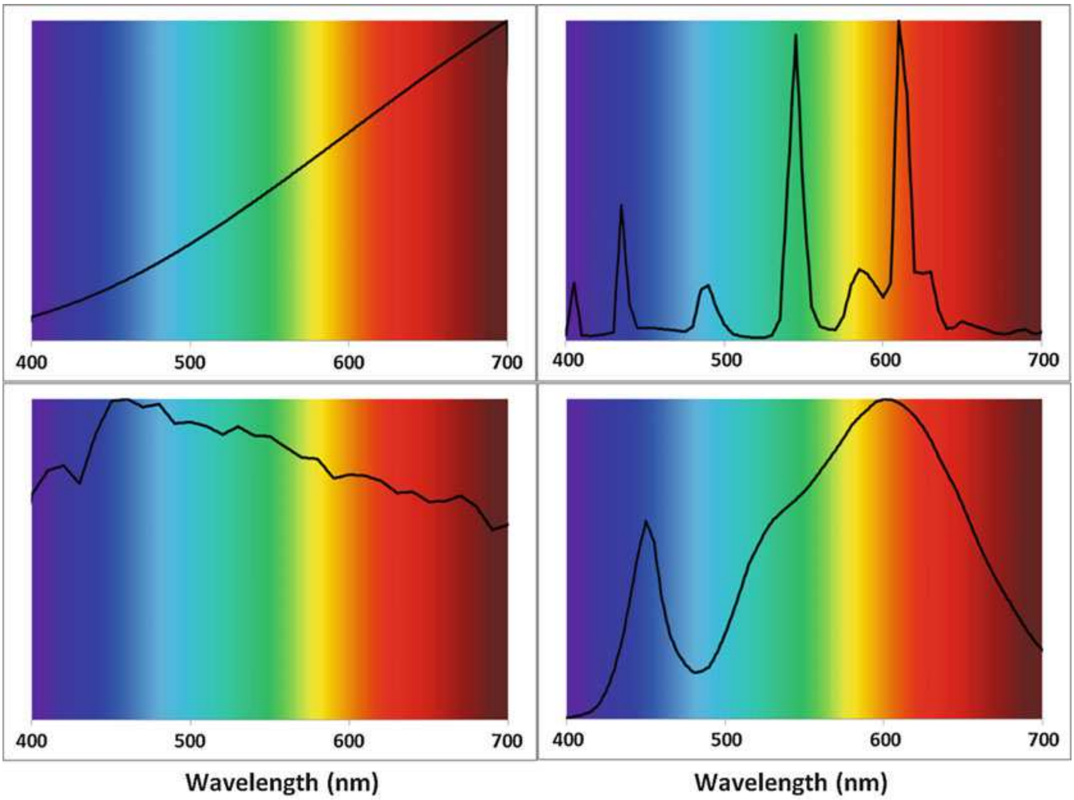
Light, Electromagnetic Spectrum, Fig. 3 Use of a prism to separate white lights into a spectrum of colors

Radiation of a single wavelength is called *monochromatic*. Except for lasers and certain specialized lamps, most sources of optical radiation emit energy over a broad wavelength region. The curve describing the power at each wavelength is called the *spectral power distribution* (SPD). A color stimulus generally has an SPD that varies with wavelength across the visible spectrum producing a color or sensation that is a shade or mixture of the colors listed in Table 2. Stimuli containing all the visible wavelengths in roughly equal proportions appear white.

This is demonstrated by passing white light through a glass prism, which spreads the light out into a spectrum of colors (see Fig. 3).

However, white light can also be produced by superimposing discrete monochromatic lights. For example, white light can be produced by superimposing red, blue, and green lights in certain proportions. This was first demonstrated by Thomas Young [3] who used this experimental finding to theorize that the human eye contained three different types of color receptors, which is known as the trichromatic theory of human color vision.

Because of this trichromacy, white light can be produced by many different SPDs. The variation in these SPDs is illustrated in Fig. 4, which shows the SPD of a typical tungsten lamp, a fluorescent lamp, a white LED source produced by a blue LED and yellow phosphor, and noon daylight. The most prevalent source of light in our natural environment - the sun, has an SPD that can change dramatically during the course of the day, from a bluish cast at noon to a reddish-orange cast at sunset. These variations in SPD of the light source are very important for visual evaluations of colored goods. For this reason, the SPDs of different phases of daylight have been standardized by the International Commission on Illumination (CIE) as a series of D illuminants. Shown in Fig. 4 is the SPD of CIE standard illuminant D65, which is average daylight with an approximate correlated color temperature of 6500 K.



Light, Electromagnetic Spectrum, Fig. 4 Relative spectral power distributions (SPDs) of four different sources of white light; CIE illuminant (if applicable) given in parentheses: *Top Left*: tungsten lamp (CIE A); *Bottom Left*: noon daylight (CIE D65); *Top Right*: fluorescent lamp (FL12); blue LED + yellow phosphor

Applications of Electromagnetic Radiation

The applications of electromagnetic radiation (emr) cover almost all aspects of our daily lives. The importance of visible light for human vision has already been discussed. Light emanating from the sun spans the solar wavelength region from about 250 nm in the UV to 2,500 nm in the near-infrared region. This solar radiation is extremely important to the energy balance of the earth and for various building design applications, such as the design of glazing materials. It is also exploited in light-based technologies, such as photovoltaics.

Light in the infrared region of the spectrum is felt as heat and is used in the design of radiant heating, solar panels, and collectors. The frequencies in the infrared region are close to the resonant vibrational frequencies in molecules and can be used for molecular identification by spectroscopic means. Similarly, the frequencies in the microwave region are close to the resonant rotational frequencies in molecules, in particular the water molecule. Since most foods contain a significant amount of water, the microwave radiation heats the food by the increased rotational motion of the interspersed water molecules. These microwaves pass through glass, ceramic, and plastic but reflect from metal which can also be used to advantage in the selection of the food container and walls of the microwave, respectively.

Light in the ultraviolet (UV) region has many important uses. In the early nineteenth century, it was called “chemical rays” because it was found that UV radiation could cause chemical changes. This was used to advantage to harden special glues in inks, coatings, and adhesives more quickly, in a process called UV curing through polymerization. The skin of our bodies needs exposure to UV with wavelengths in the region 280–315 nm (UVB) in order to stimulate the production of Vitamin D. However, too much exposure to UVB can cause skin cancers, so it is important to find the optimum exposure level. UV light with wavelengths in the region 200–280 nm (UVC) is called "germicidal UV" because it has sufficient energy to inactivate bacteria and viruses by disabling their DNA strands. For this reason, it is also used for sterilization of surfaces such as medical equipment. This type of UVC radiation is often produced by a low-pressure mercury vapour lamp (see Fig. 2). UV radiation is also needed to excite a class of molecules referred to as fluorescent-whitening agents (FWAs) or optical brighteners in manufactured white goods, such as paper, fabrics, detergents, soaps, and cosmetics, which emit in the blue portion of the visible spectrum and produce an enhanced whiteness effect. UV radiation is also of the appropriate frequencies to absorb ozone molecules in the atmosphere so very little UV radiation reaches the earth's surface.

X-rays have a higher frequency than UV radiation and can pass through the skin and soft tissue, but they do not easily pass through the bone or metal. This type of emr is used to produce photographs of bones in medical diagnostics to check for damage such as fractures. The frequencies of gamma radiation, on the other hand, are more penetrating and can destroy chemical bonds by interacting with the electrons of the constituent atoms or disrupt DNA bonds, resulting in prevention of cellular division. This can be used to advantage to kill microorganisms throughout the material. Gamma sterilization is used, for example, in sterilization of water and food products.

Other important applications of emr are radio, television, and electric current.

Cross-References

- ▶ Blackbody Radiation
- ▶ Iridescence
- ▶ Rayleigh Scattering, Mie Scattering
- ▶ Spectral Power Distribution (SPD)

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