

Chapter 1.

# THE LIGHT

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## 1.1. General remarks

It is well known that there are several types of energy: mechanical, thermal, electrostatic and electromagnetic.

- If mechanical energy is applied to a body at rest, it tends to set into motion, thus, transforming the energy applied into kinetic energy. This energy is taken along and is also transmitted to other bodies, in case it collides with them.
- Heat is a form of energy which diffuses through convection, conduction or radiation.
- When a switch is "turned on", the metallic filament of an incandescent lamp is connected by means of a potential difference. Thus, electric charge flows through the filament in a similar way pressure difference in a hosepipe makes water flow through it. Electron flow constitutes the electric current. Current is usually associated to charge movement in bridge conductors, but electric current emerges from any charge flow. When electric current diffuses through conductors and reaches a receptor, this receptor is transformed into another type of energy.
- If the body or the emitting source irradiates energy, propagation takes place by means of radiation in the form of waves\* which are those physical disturbances which diffuse in a certain medium or in the vacuum.

**Mechanical waves** diffuse this kind of energy through an elastic material medium. They are longitudinal sound waves because particle vibration coincides with their propagation direction. Two examples of this phenomenon are vibrations of spring and sounds. In a spring, vibrations propagate in only one direction. In the case of sound, vibrations propagate in three different dimensions.

**Electromagnetic waves** propagate the energy produced through oscillations of electric and magnetic fields and do not need a propagation material medium. For example, the light.

Out of the different ways waves propagate, there are several regimes. From the point of view of lighting engineering, the **periodical regime** is the one which interests us. It may be defined as regular time interval repetitions and expressed graphically as several wave forms.

Thus, wave form represents oscillations as phenomena in which physical quantity is a periodical function of an independent variable (time), whose average value is null. That is to say, we are talking about simple or fundamental harmonic functions, like the sine or the cosine, of a single, one-dimensional and transversal variable (propagated perpendicularly to the direction in which particles vibrate). In short, there is a wide range of physical, electric and electromagnetic phenomena, among which electricity, light, sound, hertzian waves or sea waves are included. Their characteristics are determined by studying sine waves. This is the reason why the concept of wave *radiation* and characteristics to define them is used.

## 1.2. Wave characteristics

### Wavelength ( $\lambda$ )

It is defined as the *distance travelled by a wave in a period*. For a transversal wave, it may be defined as the *distance between two consecutive maximums or between any other two points located in the same phase* (Fig. 1).

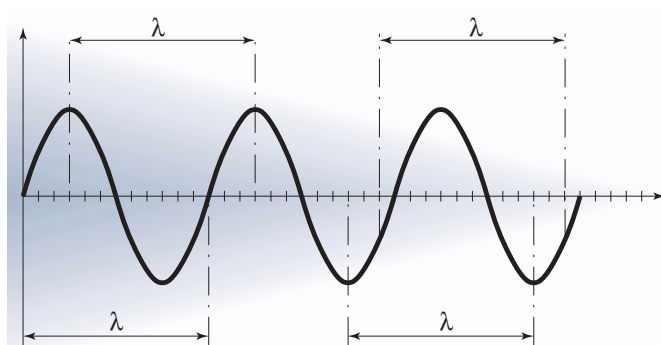


Figure 1. Wavelength  $\lambda$ .

\* Wave: Graphic expression of a periodic variation represented in amplitude and time. Amplitude is the maximum value or ordinate taken by the wave.

Wavelength is a highly important characteristic in order to classify the visible radiation spectrum, object of study in this section of LIGHTING ENGINEERING 2002.

This parameter is determined by the result of propagation velocity ( $\nu$ ), multiplied by the time it takes to cover one cycle (T Period):

$$\lambda = \nu \cdot T \quad (\text{m/s} \cdot \text{s} = \text{m})$$

### Frequency ( $f$ )

It is defined as the number of periods that take place in a time unit.

Since period is inverse to frequency,  $T = \frac{1}{f}$ , the equation above is transformed into:

$$\lambda = \frac{\nu}{f} \quad (\text{m/s} \cdot 1/\text{s}^{-1} = \text{m})$$

and, therefore, *frequency is directly proportional to propagation velocity, and inversely proportional to wavelength.*

$$f = \frac{\nu}{\lambda} \quad (\text{s}^{-1} = \text{cycles/second} = \text{Hz})$$

Wavelength decreases when frequency increases.

Frequency is stable and independent from the medium through which the wave propagates. This constitutes an important characteristic to classify electromagnetic waves.

### Propagation velocity ( $\nu$ )

Propagation velocity depends on wave type, elasticity of the medium and rigidity. If the medium is homogeneous and isotropic, propagation velocity is the same in all directions.

For example, sound propagation velocity in the air, at 20 °C, is that of 343.5 m/s, whereas electromagnetic waves propagation velocity in the vacuum is equivalent to 300 000 km/s =  $3 \cdot 10^8$  m/s.

The fundamental equation which relates propagation velocity to wavelength and frequency is

$$\nu = \lambda \cdot f \quad (\text{m} \cdot \text{s}^{-1} = \text{m/s})$$

## 1.3. Frequency spectrum

Given the fact that electromagnetic radiations share the same nature and they all propagate in the vacuum at the same velocity ( $\nu = 3 \cdot 10^8$  m/s), those characteristics that make them different are their *wavelength*, that is to say, their *frequency* ( $\nu = \lambda \cdot f$ ).

Electromagnetic radiations are the following: gamma rays, X-rays, ultraviolet radiation, light, Infrared rays, microwaves, radio waves and other radiations. The human eye is sensitive to electromagnetic radiation with wavelengths ranging approximately between 380 and 780 nm. This interval is known as **visible light**. Shortest wavelengths of the visible spectrum correspond to violet light, and the longest, to red light. Between these two extremes are all the colours found in the rainbow (Fig. 2). Electromagnetic waves have slightly shorter wavelengths when compared to visible light and are known as ultraviolet rays. Those with slightly longer wavelengths are known as infrared waves. Thermal radiation emitted by bodies at a normal temperature is placed in the infrared region of the electromagnetic spectrum. There are no limits in electromagnetic radiation wavelength, which is the same as stating that all wavelengths (or frequencies) are possible from a theoretical point of view.

It must be taken into account that those wavelength intervals (or frequency ones) in which the electromagnetic spectrum divides sometimes are not well defined and often, they overlap. For example, electromagnetic waves with wavelengths of the order of 0.1 nm. are frequently named X-rays. Nevertheless, if originated from nuclear radioactivity, they are called Gamma rays.

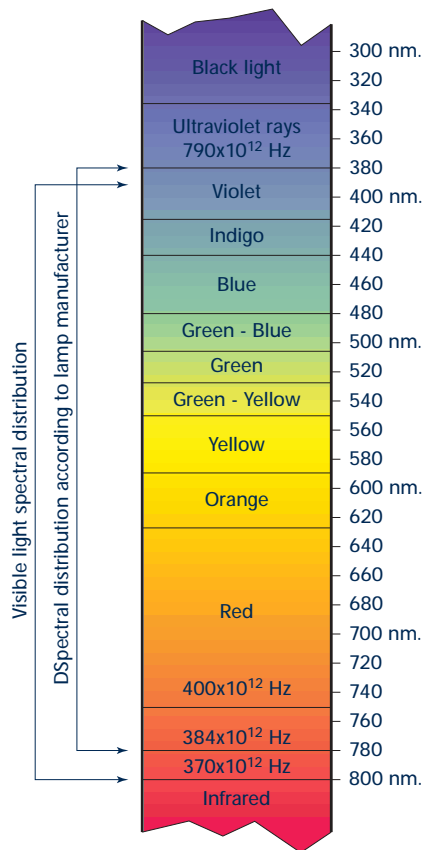


Figure 2. Classification of visible spectrum.

Lamp manufacturers usually give radio spectrometrical curves with values ranging between 380 nm. and 780 nm. As we have shown, apart from the meter, nanometer (nm.) is also used in order to express wavelengths, as well as other units like Angstrom ( $\text{\AA}$ ) and micron ( $\mu\text{m}$ ).

$$1 \mu\text{m.} = 10^{-6} \text{ m}$$

$$1 \text{ nm.} = 10^{-9} \text{ m}$$

$$1 \text{ \AA.} = 10^{-10} \text{ m}$$

### Radiation of a continuous spectrum source

All bodies radiate energy in an ample field of wavelength at any temperature except for absolute zero. This radiation is known as *incandescence* or *temperature radiation*. Sources of incandescent artificial light are:

- A flame from combustion, like a candle, oil candle, etc.
- A red-hot ingot or steel bar.
- An *incandescent* lamp filament, as the most common source to produce artificial light.

Incandescence is applied to types of radiation associated with temperature.

The spectroradiometer is used to know how the radiated potency is distributed between wavelengths. The spectroradiometrical function or spectral distribution curve obtained is indicated in Fig. 3. Wavelengths in nm. are placed in the abscissas, and values related to energy, with respect to the maximum radiated understood as 100%, are placed in the ordinates.

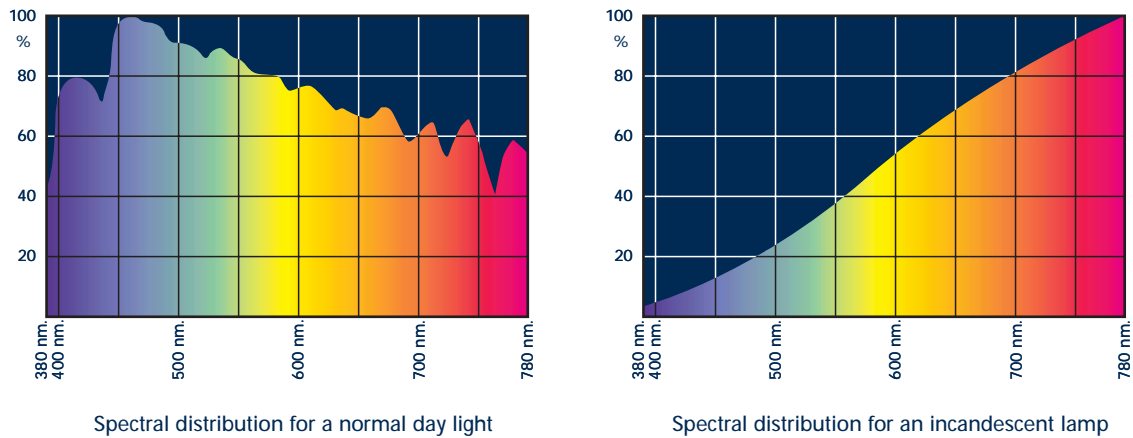


Figure 3

#### Radiation of a discontinuous spectrum source

Radiant energy of a gaseous discharge source, such as the ones of high pressure sodium, high pressure mercury, argon, neon, etc., consists in a radiation integrated by small wavelength intervals which may be called emission peaks.

Each gas has a wavelength characteristic of its own radiation which depends on the gas molecular structure through which discharge takes place. This kind of discharge is usually called **luminescence** and it is characterised by *temperature independent radiation types*. The most common luminous sources or discharge lamps are fluorescent tubes: high pressure mercury, high pressure sodium and induction ones.

As for incandescence, the spectroradiometer is used to obtain the spectral distribution curve. The spectroradiometer function obtained is indicated in Fig. 4. Wavelengths in nm. are placed in the abscissas, and values related to energy, with respect to the maximum radiated understood as 100%, are placed in the ordinates.

Also, the specific potency in mW/nm.wavelength is usually given in the ordinates.

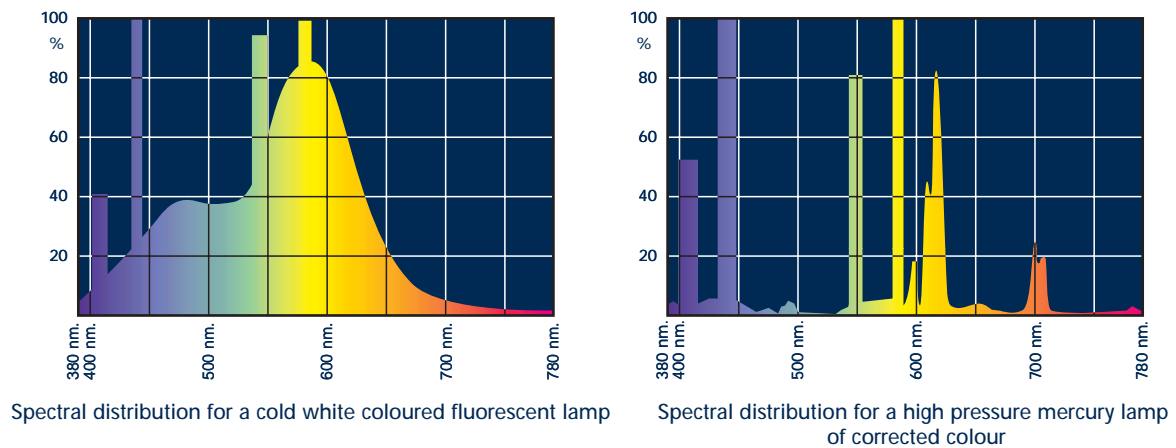


Figure 4

### 1.4. Dual nature of light

Light has intrigued humankind for centuries. The most ancient theories considered light as something *emitted* by the human eye. Later on, it was understood that light should come from the objects seen and that it entered the eye producing the feeling of vision. The question of whether light is composed by a beam of particles or it is a certain type of wave movement has frequently been studied in the history of science. Between the proponents and defendants of the **corpuscular theory of light**, the most influential was undoubtedly Newton. Using the above mentioned theory, he was able to explain the laws of reflection and refraction. Nevertheless, his deduction of the law of refraction was based on the hypothesis that light moves more quickly in water or in glass than in air. Some time later, the hypothesis was proved to be wrong. The main proponents of the **wave theory of light** were Christian Huygens and Robert Hooke. Using

their own theory of wave propagation, Huygens was able to explain reflection and refraction supposing that light travels more slowly in glass or in water than in air. Newton realized about the advantages of the wave theory of light, particularly because it explained colours formed by thin films, which he had studied very thoroughly. Notwithstanding, he rejected the wave theory due to the apparent rectilinear propagation of light. In his time, diffraction of the luminous beam, which allows to evade objects, had not yet been observed.

Newton's corpuscular theory of light was accepted for more than a century. After some time, in 1801, Thomas Young revitalized the wave theory of light. He was one of the first scientists to introduce the idea of interference as a wave phenomenon present both in the light and in the sound. His observations of interferences obtained from light were a clear demonstration of their wave nature. Nevertheless, Young's research was not known by the scientific community for more than ten years. Probably, the most important breakthrough regarding a general acceptance of the wave theory of light is due to the French physicist Augustin Fresnel (1782-1827), who conducted thorough experiments on interference and diffraction. He also developed a wave theory based on a solid mathematical foundation. In 1850, Jean Foucault measured the speed of light in water and checked that it is slower than in air. Thus, he finally destroyed Newton's corpuscular theory of light. In 1860, James Clerk Maxwell published his electromagnetic mathematical theory which preceded the existence of electromagnetic waves. These waves propagated with a calculated speed through electricity and magnetism laws which was equivalent in value to  $3 \times 10^8$  m/s, the same value than the speed of light. Maxwell's theory was confirmed by Hertz in 1887 who used a tuned electric circuit to generate waves and another similar circuit to detect them. In the second half of the 19th century, Kirchoff and other scientists applied Maxwell's laws to explain interference and diffraction of light and other electromagnetic waves and support Huygens' empirical methods of wave construction on a solid mathematical basis.

Although wave theory is generally correct when propagation of light is described (and of other electromagnetic waves), it fails when other light properties are to be explained, specially the interaction of light with matter. Hertz, in a famous experiment in 1887 confirmed Maxwell's wave theory, and he also discovered the photoelectric effect. Such an effect can also be explained by means of a model of particles for light, as Einstein proved only a few years later. This way, a new corpuscular model of light was introduced. The particles of light are known as photons and energy  $E$  of a photon is related to frequency  $f$  of the luminous wave associated by Einstein's famous ratio  $E = h \cdot f$  ( $h$  = Planck's constant). A complete understanding of dual nature of light was not achieved before the 20's in the 20th century. Experiments conducted by scientists of the time (Davisson, Germer, Thompson and others) proved that electrons (and other "particles") also had a dual nature and presented interference and diffraction properties besides their well-known particle properties. In brief, the modern theory of quantum mechanics of luminous radiation accepts the fact that *light* seems to have a dual nature. On the one hand, *light* propagation phenomena find a better explanation within Maxwell's electromagnetic theory (electromagnetic wave fundamental nature). On the other hand, mutual action between *light* and matter, in the processes of absorption and emission, is a photoelectric phenomenon (corpuscular nature).

