OPTICAL SOURCES AND DETECTORS

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Contents

Summary

This chapter includes consideration of light sources and detectors. It includes the laws of the thermal radiation, optical units, radiometry and photometry. The physical and technical characteristics of the various sources of visible, ultraviolet and infrared light are considered. Special attention is given to lasers, i.e. to the physical basics of their operation and to main their properties and characteristics.

The physical principles of light detection in the infrared, visible and ultraviolet regions are considered. Depending on the type of radiation interaction with sensitive element the detectors can be divided in the thermal and photon detectors. Their figures of merit are analyzed. Thermal detectors have the flat spectral and relatively low speed response, and they are working at ambient temperature. Among them the pyroelectric ones and the

bolometers are in wide use. Photon detectors have selective spectral response and high speed. Besides they need cooling especially in the infrared region. The single photon counting can be realized with the photon detectors like photomultipliers and semiconductor detectors. The detector arrays based on the CCD elements, on the photodiodes, on the photoconductors or on the microbolometers are developed to use in imaging systems in the visible and infrared regions.

1. Introduction

Light is the basis of the science of optics and optical instruments. Light influences the way we live today in ways that could never have been imagined just a few decades ago.

Developments in optics in the XX century have had a profound influence on science and technology. Examples include the optical lithography techniques used to make computer chips, high-resolution microscopes, infrared sensors and highly efficient lighting sources. The invention of laser has led to majority of its applications. It is, of course, the unique properties of the laser – monochromaticity, directionality, coherency, and brightness – that account for its wide acceptance and usefulness. The broad class of applications that involve the interaction of lasers with matter includes the industrial machining and processing of materials, therapeutic and surgical uses in medicine, laser-driven energy sources, scribing, and microfabrication in semiconductor and computer technologies. The equally broad class that involves lasers and information includes information processing, optical sensing and ranging, optical communication, entertainment, printers and copiers, metrology, and alignment facilitators in construction and agriculture.

As we moved into the XXI century, light will play an even more critical role in the way we communicate, in the way we practice medicine and in the tools we use to explore the frontiers of science.

The paper is devoted to physical description of production and measurement of light, i.e. to optical sources and detectors.

Sources and detectors of electromagnetic radiation can be classified on the basis of their spectral range and the strength of signal produced (sources) or detected (detectors).

A. Optical Sources

2. Spectrum of Optical Radiation

Optical spectrum occupies the range in wavelengths and frequencies from $\lambda = 1$ mm, $\nu = 3\times10^{11}$ Hz up to $\lambda = 10$ nm, $\nu = 3\times10^{16}$ Hz (1 nm $=10^{-9}$ m). By convention optical radiation is subdivided into three parts – visible, ultraviolet and infrared light.

Visible light

Visible light, the most familiar form of electromagnetic waves, may be defined as that part of the electromagnetic spectrum that the human eye can detect. Light is produced by the rearrangement of electrons in atoms and molecules, as we shall discuss below.

The various wavelengths of visible light are classified by color, ranging from violet ($\lambda \cong 4\times10^{-7}$ m) to red ($\lambda \cong 7\times10^{-7}$ m). The eye's sensitivity is a function of wavelength, the sensitivity being a maximum at a wavelength of about 5.6×10^{-7} m (yellow-green).

Ultraviolet light

Ultraviolet light is the name given to wavelengths ranging from approximately 1×10^{-7} m (380 nm) down to 4×10^{-7} m (60 nm). The sun is an important source of ultraviolet light. Ultraviolet radiation is often used to kill bacteria and viruses. Ultraviolet lamps are used to sterilize hospital operating rooms and surgical instruments. Low-energy ultraviolet lamps are sometimes placed above grocery meat counters to reduce spoilage.

Infrared light

Radiation with wavelengths ranging approximately from 760 nm to 1 mm is usually named as infrared light. Note that radiation of human body falls in the infrared range and this provides the basis for night-vision techniques.

In the visible spectrum line radiations are emitted by excited vapors or gasses. A hot solid emits radiation which extends over a continuous range of frequencies.

Three line sources in the visible and near visible will serve as samples: (1) a sodium arc lamp with its yellow doublet provides a source for the measurement of wavelength differences by use of interferometers; (2) a mercury arc provides the famous green line and sources in the near ultraviolet; (3) a cesium lamp has two intense lines in the near infrared.

3. Optical Units: Radiometry and Photometry

Electromagnetic radiation may vary in wavelength (or frequency) and in "strength." Variations in strength are described in more precise physical terms, which have developed in the areas called radiometry and photometry.

Radiometry is the science of measurement of electromagnetic radiation. In the discussion we present the radiometric quantities or physical terms used to characterize the energy content of radiation.

Radiometry applies to the measurement of all radiant energy. Photometry, on the other hand, applies only to the visible portion of the optical spectrum. Whereas radiometry involves purely physical measurement, photometry takes into account the response of the human eye to radiant energy at various wavelengths and so involves psycho-physical measurements. The distinction rests on the fact that the human eye, as a detector, does not have a "flat" spectral response; that is, it does not respond with equal sensitivity at all wavelengths. If three sources of light of equal radiant power but radiating blue, yellow, and red light, respectively, are observed visually, the yellow source will appear to be far brighter than the others. When we use photometric quantities, then, we are measuring the properties of visible radiation as they appear to the normal eye, rather than as they appear to an "unbiased" detector. Since not all human eyes are identical, a standard response has been determined by the International Commission on Illumination (CIE) and is reproduced in Figure 1. The relative response or sensation of brightness for the eye is plotted versus wavelength, showing that peak sensitivity occurs at the "yellow-green" wavelength of 555 nm. Actually the curve shown is the luminous efficiency of the eye for photopic vision, that is, when adapted for day vision. For lower levels of illumination, when adapted for night or scotopic vision, the curve shifts toward the green, peaking at 507 nm. It is interesting to note that human color sensation is a function of illumination and is almost totally absent at lower levels of illumination.

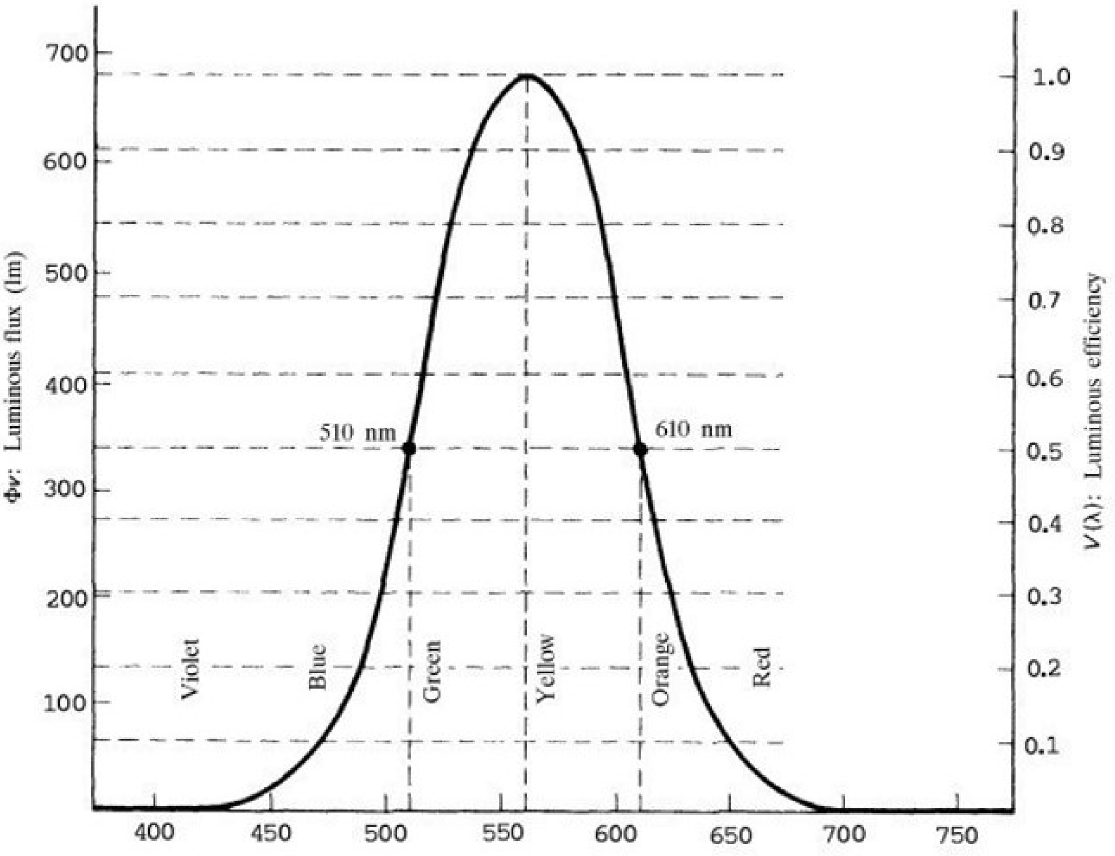

Figure 1: CIE luminous efficiency curve for light-adapted eye (photopic eye response). The luminous flux corresponding to 1 W of radiant power at any wavelength is given by the product of 683 lm and the luminous efficiency at the same wavelength: $F_v(\lambda)=683V(\lambda)$ lm.

The spectral distribution of a light source can be expressed by different wavelength-dependent quantities. The most useful spectral distribution function for a light source is the spectral radiance, $w(\lambda)$, which is the radiant power per unit area, unit solid angle, and unit wavelength interval. Like the radiance and the brightness (see below), the spectral radiance cannot be increased by optical means, but is decreased by absorption and reflection losses and optical aberrations.

In general, a light source does not radiate uniformly and isotropically, and hence the spectral radiance varies over the source area A and the emission solid angle Ω. The concepts and units of the other spectral functions and their relation to the spectral radiance are given below.

Spectral radiance: $w(\lambda)$ [W/(m^2·sr·nm)]*Spectral intensity*: $i(\lambda) = \int w(\lambda) dA$ [W/(sr·nm)]*Spectral flux density*: $\varphi(\lambda) = \int w(\lambda) d\Omega$ [W/(m^2·nm)]

Spectral flux: $f(\lambda) = \iint w(\lambda) dA d\Omega$ [W/nm]

The radiometric quantities of radiance, intensity, flux density, and flux are obtained by integrating the corresponding spectral functions over the wavelength interval of interest.

Radiance: $L = \int_{\lambda_1}^{\lambda_2} w(\lambda) d\lambda$ [W/(cm^2·sr)]

Intensity: $I = \int L dA = \int_{\lambda_1}^{\lambda_2} i(\lambda) d\lambda$ [W/sr]

Flux density: $\Phi = \int L d\Omega = \int_{\lambda_1}^{\lambda_2} \varphi(\lambda) d\lambda$ [W/cm^2]

Note that the flux density at an irradiated area is sometimes called "irradiance." At distances large compared with the source dimensions, the irradiance perpendicular to the radius vector is a measure of the source intensity

Flux: $F = \iint W dA d\Omega = \int_{\lambda_1}^{\lambda_2} f(\lambda) d\lambda$ [W]

When radiometric concepts are used, the wavelength interval in question has to be specified. Depending on the given problem, the quantities λ_1 and λ_2 may represent the transmission range of a monochromator, or all the wavelengths below a threshold value, or even the total electromagnetic spectrum.

Radiometry is concerned with the total energy content of the radiation, while photometry examines only the radiation that humans can see. Thus, the most common units in radiometry is the watt (W), which measures radiant flux F (power), while the fundamental standard unit in photometry is the luminous intensity I_v named the candela (cd). The candela is defined by radiation that eye can see and that is emitted from a black body (see below) at the temperature of solidification of platinum (2040.75 K) at normal pressure (101325 Pa). A candela is one-sixtieth of the luminous intensity of one square centimeter of such a source. All others photometric units are derived from the standard luminous intensity (cd).

The photometric analogy to the radiometric radiance L is the quantity of brightness (luminance) L_v or *B*.

$$B = 683(\text{lumen/W})\int_0^\infty w(\lambda)V(\lambda)d\lambda \qquad [\text{lm/(m}^2\text{sr)}],$$

Here the spectral radiance is weighted by the standard visibility function $V(\lambda)$ (CIE luminous efficiency curve) and the integration goes over the whole spectrum. The function $V(\lambda)$ represents the relative spectral sensitivity of an average human "day-light" eye measured by Gibson and Tyndall and was adopted as CIE standard in 1924. Main photometric quantities and units are listed below.

Luminous intensity: $I_v = \int BdA = 683(\text{lm/W})\int_0^\infty i(\lambda)V(\lambda)d\lambda \qquad [\text{cd}]=[\text{lumen/sr}]$

[candela(cd)]=[lumen/sr]

Luminous flux density: $\Phi_v = \int Bd\Omega = 683(\text{lm/W})\int_0^\infty \varphi(\lambda)V(\lambda)d\lambda \quad [\text{lumen/cm}^2)]$

The unit of luminous flux is the lumen (lm), which is the flux emitted per unit solid angle by a uniform point source of one candela. Such a source produces a total luminous flux of 4π lm.

Lumenous flux: $F_v = \iint BdAd\Omega = 683(\text{lm/W})\int_0^\infty f(\lambda)V(\lambda)d\lambda \quad [\text{lm=cd.sr}].$

The luminous efficiency is the ratio of (light output)/(power input), given in units of lumen/W. The maximum value of 683 lm/W would describe an ideal lamp which converts the electrical power completely into radiation of 555 nm wavelength.

4. Thermal Radiation

4.1. Black-body Radiation

A black body is an abstraction, it is an ideal absorber: all radiation falling on a black body, irrespective of wavelength or angle of incidence, is completely absorbed. It follows that a black body is also a perfect emitter: no body at the same temperature can emit more radiation at any wavelength or into any direction than a black body. Black bodies are approached in practice by blackened surfaces and by tiny apertures in radiating cavities.

The laboratory version of a black body is a hohlraum which is a big box with a small hole. The box is maintained at a uniform, well-defined temperature. For a completely closed box in thermal equilibrium the radiation density inside can be calculated rigorously and is independent of the box material. If the hole is negligibly small compared with the inside wall surface, the number of photons escaping through the hole is negligible compared with the total number of absorption-emission and reflection processes in the box; thus the equilibrium will not be disturbed by the radiation output. Hence, a hot hohlraum radiator can be operated in a much colder environment and yet the calculations for thermal equilibrium are valid.

In thermal equilibrium with the environment a body can only emit as much as it absorbs; thus the spectral radiance of a real body is given by the black body value multiplied by the absorptance (Kirchhoff’s law).

The black body is the primary radiation standard. Any source with easily reproducible light out put can be used as a secondary standard after having
been calibrated by comparison with the black body radiator.

4.2. Laws of Thermal Radiation

The spectral radiant exitance M_λ of a blackbody can be derived on theoretical grounds. It was first so derived by Max Planck, who found it necessary to postulate quantization in the process of radiation and absorption by the blackbody. The result of this calculation is given by

$$M_\lambda = \frac{hc^2}{\lambda^5}\left(\frac{1}{e^{hc/\lambda kT} - 1}\right), \qquad (1)$$

where the physical constants *h*, *c*, and *k* represent the Planck constant, the speed of light in vacuum, and the Boltzmann constant, respectively. When the known values of these constants are used, the result is

$$M_e(\lambda,T) = \frac{3.745\times 10^8}{\lambda^5}\left(\frac{1}{e^{14388/\lambda T} - 1}\right)(\mathrm{W/m^2 \mu m}) \qquad (2)$$

where λ is in micrometers and *T* is in Kelvin. The quantity M_λ is plotted in Figure 2 for different temperatures. The spectral radiant exitance is seen to increase with absolute temperature at each wavelength.

The peak exitance also shifts toward shorter wavelengths with increasing temperature, falling into the visible spectrum (dashed vertical lines) at T = 5000 and 6000 K. The variation of $\lambda_{\max}$, the wavelength at which M_λ peaks, with the temperature can be found by differentiating M_λ with respect to λ and setting this equal to zero. The result is the Wien displacement law, given by

$$\lambda_{\max} T = \frac{hc}{5k} = 2.88\times 10^3 (\mathrm{\mu m K}) \qquad (3)$$

and is indicated in Figure 1 by the dashed curve. If, on the other hand, the spectral exitance of Eq.(1) is integrated over all wavelengths, the total radiant exitance or area under the blackbody radiation curve ,at temperature *T* is

$$M = \sigma T^4 \qquad (4)$$

known as the Stefan-Boltzmann law, with σ as the Stefan-Boltzmann constant, equal to $5.67 \times 10^{-8} W / m^2 K^4$.

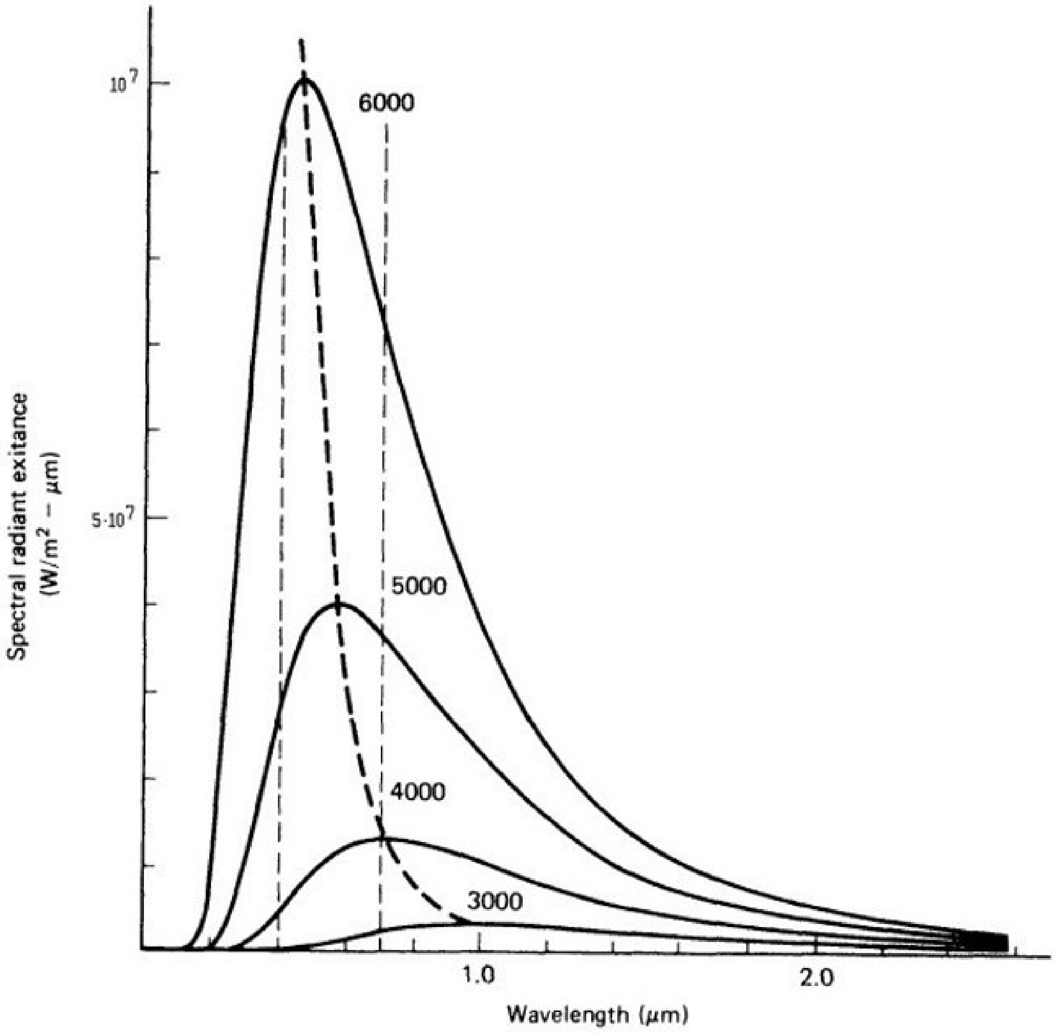

Figure 2: Blackbody radiation spectral distribution at four Kelvin temperatures. The vertical dashed lines mark the visible spectrum, and the dashed curve connecting the peaks of the four curves illustrates the Wien displacement law.

The radiation from real surfaces is always less than that of the blackbody or Planckian source and is accounted for quantitatively by the emissivity ε. Distinguishing now between the radiant exitance M of a measured specimen and that of a blackbody M_{bb} at the same temperature, we define

$$\varepsilon(T)=M/M_{bb} \tag{5}$$

If the radiant exitance of the blackbody and the specimen are compared in various narrow wavelength intervals, a spectral emissivity is calculated, which is not in general a constant. In those special cases where the emissivity is independent of wave-length, the specimen is said to be a graybody. In this instance the spectral exitance of the specimen is proportional to that of the blackbody and their curves are the same except for a constant factor. The spectral radiation from a heated tungsten wire, for example, is close to that of a graybody with ε= 0.4-0.5.

4.3. Color Temperature

All practical thermal radiators give emission curves over the spectrum which may be similar in shape to the black body curves, but more generally they show maxima and minima depending on the nature of the incandescent material; i.e., they are selective, but the ordinates of the curves always lie below those of a black body at the same temperature.

The temperatures of bodies estimated from their total radiation using Stefan's Law are called radiation temperatures. If the temperatures are estimated from the visible brightness of the emitter as seen by the eye they are called brightness temperatures. If, however, the shape of the emission curve in the visible region is compared with the shape of the black body radiation curve in the same region and the best possible fit obtained they are called color temperatures. Color temperatures are usually greater, and brightness temperatures usually less, than the absolute temperature.

Color temperatures are important in many applications of photography and it is usual to state the color temperature of a source for that purpose. The color rendering of sources depends on the color temperature.

Standard electric lamps are available, whose spectral distribution of energy has been carefully determined and these lamps are used to calibrate simpler instruments for the determination of color temperatures. In portable optical pyrometers, for example, the light from the hot source is brought to a focus in the same plane as a heated carbon or tungsten filament. The temperature of the filament is adjusted by altering the current through it until the filament becomes invisible against the background of light from the hot source. The current-temperature relation of the filament is found by calibration against a standard source. For high color temperatures of source red filters are used to obtain the match.

Thus, dlackbody radiation is used to establish a color scale in terms of absolute temperature alone. The color temperature of a specimen of light is then the temperature of the blackbody with the closest spectral energy distribution. In this way, a candle flame can be said to have a color temperature of 1900 K, whereas the sun has a typical color temperature of 5500 K.

5. Sources of Optical Radiation

Sources of light may be natural, as in the case of sunlight and skylight, or artificial, as in the case of incandescent or discharge lamps. Light from various sources may also be classified as monochromatic, spectral line, or continuous. The way in which energy is distributed in the radiation determines the color of the light and, consequently, the color of surfaces seen under the light. Anyone who has used a camera is aware that the actual color response of film depends on the type of light used to illuminate the subject.

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Biographical Sketches

Mitrofanov Alexandr Viktorovich graduated from the Moscow Institute of Physics and Technology (MIPT) in 1969. He received his Doctor of Science degree in 1976 from Kapitza Institute for Physical Problems. Then he spent about 25 years with Lebedev Physical Institute working on the Extreme Vacuum Ultraviolet aerospace optics and solar X-Ray astronomy. Total number of scientific publications is more then 50. He authored several articles in the popular student magazine of mathematics and science “Quantum”.

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