2.1 Definition and measurement of radiometric quantities

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2.1.1 Introduction

Radiometry is the science and technology of the measurement of electromagnetic energy. Here we confine ourselves on the subfield of optical radiometry which covers the measurement of electromagnetic radiation in the wavelength range from about 0.01 μm to 1000 μm. Radiometric quantities are derived from the quantity energy. The corresponding photometric quantities on the other hand involve the additional evaluation of the radiant energy in terms of a defined weighting function, usually the standard photometric observer. In the following only the definitions of the radiometric quantities are explained in detail. Starting from the radiant energy the other fundamental radiometric quantities radiant power, radiant excitance, irradiance, radiant intensity, and radiance are derived by considering the additional physical quantities time, area, and solid angle.

The radiometric quantities defined in abstract terms are practically embodied by radiometric standards. Radiometry is based on primary detector standards and primary source standards. Primary detector standards are mostly electrical-substitution thermal detectors whereas for primary source standards the emitted radiant power is accurately calculable. For the radiometric measurement of cw laser emission radiation detectors or radiometers calibrated against primary detector standards are the preferred secondary standards. The detection principle of the radiometers could be thermal (thermopiles, bolometers, and pyroelectric detectors) or photoelectric (semiconductors). As secondary standards for pulsed laser radiation mostly thermally absorbing glass-disk calorimeters are used. These standards are derived from the cw standards using accurately measured shuttering of the laser radiation to produce pulses of known radiant energy.

2.1.2 Definition of radiometric quantities

Radiometric and photometric quantities are represented by the same principal symbol and may be distinguished by their subscripts. While radiometric quantities either have the subscript "e" or no subscript (as in the whole Chap. 2.1), photometric quantities have the subscript "v", where "e" stands for "energetic" and "v" for "visible". The most frequently used radiometric quantities are listed in Table 2.1.1 together with their symbols, defining equations, and units. The additional physical quantities applied in Table 2.1.1 are the time t, the element of solid angle $\mathrm{d}\,\omega$, and the angle θ between the line of sight and the normal of the radiating or receiving surface with the area element $\mathrm{d}A$, see Fig.2.1.1.

In the case that the quantities are functions of wavelength their designations must be preceded by the adjective "spectral". For example, the symbol for spectral radiance is $L(\lambda)$. This has to be well distinguished from the convention for the spectral concentration of a quantity, which is also preceded by the adjective "spectral". In that case, however, the symbol has the subscript λ, i.e. $\mathrm{d}L/\mathrm{d}\lambda = L_\lambda$.

Table 2.1.1. Radiometric quantities, their defining equations and units.

Quantity	Symbol	Defining equation	Unit
Radiant energy	Q		J
Radiant power	Φ	$\Phi = \mathrm{d}\,Q/\mathrm{d}t$	W
Radiant excitance	M	$M = \mathrm{d}\,\Phi/\mathrm{d}A$	W m^{-2}
Irradiance	E	$E = \mathrm{d}\,\Phi/\mathrm{d}A$	W m^{-2}
Radiant intensity	I	$I = \mathrm{d}\,\Phi/\mathrm{d}\,\omega$	W sr^{-1}
Radiance	L	$L = \mathrm{d}^2\,\Phi/(\cos\,\theta\,\mathrm{d}A\,\mathrm{d}\,\omega)$	W m^{-2} sr^{-1}

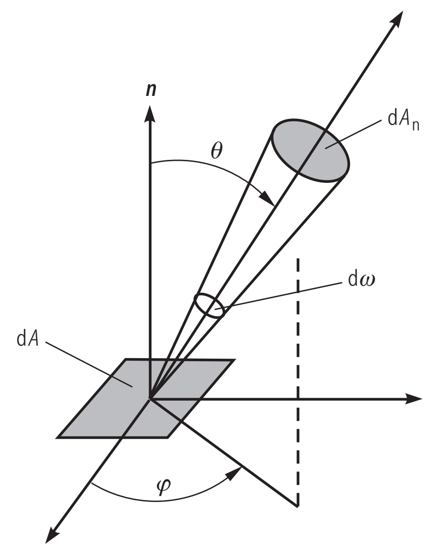

Fig. 2.1.1. Geometry for definition of the radiance.

To explain the defining equations given in Table 2.1.1 a radiation source of finite extent is considered. If we surround the radiation source with a closed surface and calculate the radiant energy Q penetrating the surface per unit time we get the total radiant power Φ emitted by the source. For clarity, the above mentioned symbols for the spectral properties of the radiation are omitted in this chapter. The radiant power per unit area of the radiation source associated with the emission into the hemispheric space above dA is defined as the radiant excitance M. At this point it is appropriate to introduce the radiation incident from all directions in the hemispheric space above the surface of a detector. The irradiance E is defined as the radiant power incident on a surface per unit area of the surface. The irradiance represents also the energy which propagates per unit time through the unit area perpendicular to the direction of energy transport. This is known as the density of energy flow identical to the magnitude of the Poynting vector averaged over time.

Coming back to the source-based radiometric quantities we consider now the radiant power proceeding from a point source per unit solid angle $\mathrm{d}\,\omega$ in a specified direction. The corresponding quantity appropriate especially for nearly point-shaped sources is denoted as radiant intensity I. If we generalize and consider again a source of finite extent the directional nature of radiation has to be taken into account accurately. From Fig. 2.1.1 we formally define as radiance L the radiant power emitted in the (θ, φ) direction, per unit area of the surface normal to this direction and per unit solid angle. Note that the area $\mathrm{d}A_\mathrm{n}$ used to define the radiance is the component of dA perpendicular to the direction of the radiation. This projected area is equal to $\cos\theta\,\mathrm{d}A$ and in effect, this is how dA would appear to an observer situated on the surface in the (θ, φ) direction.

Although the directional distribution of surface emission varies according to the nature of the surface, there is a special case which provides a reasonable approximation for many surfaces. For an isotropically diffuse emitter the radiance is independent of direction:

$$L(\theta,\varphi) = L\ . \tag{2.1.1}$$

Such an emitter is denoted as a lambertian radiator which emits in accordance with Lambert's cosine law:

$$I(\theta) = I(0)\cos\,\theta\ . \tag{2.1.2}$$

The radiant intensity of a perfectly diffuse surface element in any direction varies as the cosine of the angle between that direction and the normal to the surface element. It is noted that this law is consistent with the definitions of radiance and radiant intensity given in Table 2.1.1. It may be helpful to derive the relationship between radiance and radiant excitance for a lambertian radiator. The radiant excitance into the hemispheric space above $\mathrm{d}A$ is calculated from the radiance by integration over the solid angle $\mathrm{d}\,\omega = \sin\,\theta\ \mathrm{d}\theta\,\mathrm{d}\varphi$:

$$M = \frac{\mathrm{d}\,\Phi}{\mathrm{d}A} = \int_0^{2\pi}\int_0^{\pi/2} L(\theta,\varphi)\ \cos\theta\ \sin\theta\,\mathrm{d}\theta\,\mathrm{d}\varphi\ . \tag{2.1.3}$$

By removing $L(\theta,\varphi)$ from the integrand according to (2.1.1) and performing the integration we get

$$M = \pi\,L\ . \tag{2.1.4}$$

Note that the constant appearing in the above expression is π, not 2π, and has the unit steradian (sr).

2.1.3 Radiometric standards

2.1.3.1 Primary standards

Depending on the application primary source and primary detector standards are used to establish radiometric scales. Black-body radiators of known temperature with calculable spectral radiance are operated as primary source standards at temperatures up to about 3200 K [96Sap]. Due to the steep decrease of their Planckian radiation spectrum in the UV spectral range radiometry with black-body radiators is limited to wavelengths above 200 nm. In comparison with a black-body radiator, the maximum of the synchrotron radiation spectrum emitted by an electron storage ring is shifted to shorter wavelengths by several orders of magnitude [96Wen]. In a storage ring electrons move with nearly the velocity of light along a circular trajectory and emit a calculable radiant power through an aperture stop situated near the orbital plane. Radiometry can thus be extended into the X-ray region up to photon energies of 100 keV.

Electrical-substitution thermal detectors operated at ambient temperature have been the most frequently used primary detector standards. However, their performance is limited by the thermal properties of materials at room temperature resulting in complicated corrections that have to be applied. Hence, their uncertainties remain near 0.1 % to 0.3 % [89Fro, 79Wil]. Cryogenic radiometers have been developed to satisfy the increasing demands for more accurate detector standards from users especially in new and expanding fields of optical fibers, laser technology, and space science. Today, these instruments with absorption cavities at nearly the temperature of liquid helium

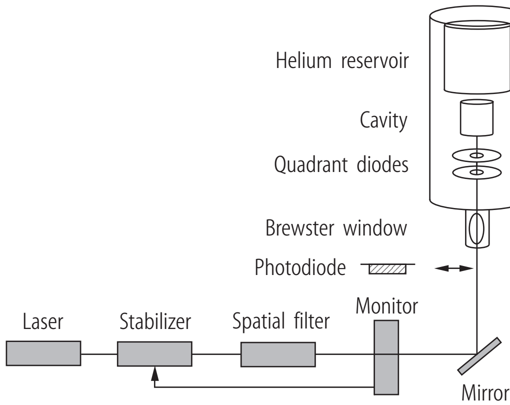

Fig. 2.1.2. Cryogenic radiometer for the calibration of photodiodes. The stabilized laser beam enters the cryostat via a Brewster window and is aligned by quadrant photodiodes. In the cavity the laser radiation is absorbed and electrically substituted.

are the most accurate among all primary standards, with relative uncertainties of less than 0.01 % [85Qui, 96Fox]. The principle of operation of both the cryogenic radiometers and the instruments at ambient temperature is that a thermometer measures the temperature rise of an absorption cavity, relative to a constant-temperature heat sink, during radiant and electrical heating cycles. By adjusting the electrical power so that the absorption cavity temperature rise is the same for both types of heating, the radiant power can be equated to the easily measured quantity of electrical power. For cryogenic radiometers the corrections due to the limited absorptance of the cavity, the lead heating of electrical connections, the radiative heat loss, and the background radiation can be made sufficiently small to reach very accurate equivalence of optical and electrical heating [96Fox]. Today, high-precision calibrations of laser radiometry secondary standards are mostly traceable to cryogenic radiometers. In Fig. 2.1.2 a typical experimental arrangement for the calibration of transfer photodiodes is shown [93Fu].

2.1.3.2 Secondary standards

Secondary standards serve to disseminate a metrologic scale or quantity to the user in science and industry. In this section, first, the common detectors used in the secondary standards for laser radiometry are shortly described, and second, some examples for laser radiometers and calorimeters are given. The detection principle of the secondary standards is usually thermal or photoelectric. The thermal detectors have the remarkable advantage of a flat spectral responsivity function which makes the calibration for different laser wavelengths not necessary or at least easier compared to that of photoelectric detectors. Among the thermal detectors we distinguish between thermopile detectors, bolometric and pyroelectric detectors.

A thermopile consists of a number of thermocouples in series to provide a thermoelectric voltage proportional to the temperature difference between the receiver and its thermal environment. Its optimization in detector applications has received considerable attention [68Smi, 58Sch, 70Ste]. At this point the term responsivity s is introduced which is the ratio of the detector output to the detector input. Whereas the detector input is a radiometric quantity, the detector output is usually an electrical quantity, for example current, voltage, or change in resistance. In order to optimize the responsivity of a thermopile one has to maximize the Seebeck coefficient of the two materials used for each thermocouple, the thermal resistance between the receiver and the environment, and the absorptance of the surface. The materials used for thermocouples are either metals, alloys, or semiconductors, for examples see [89Hen].

A bolometer is a temperature transducer based on the change of electrical resistance with temperature. The important quantity is the temperature difference between the receiver and its

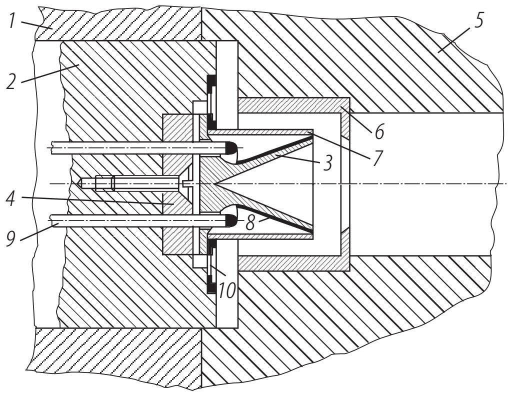

Fig. 2.1.3. Cross section of a cone-shaped laser radiometer. *3*: blackened cone, *6*: aperture, *7*: heat protection tube, *8*: electrical heater, *9*: electrical connections, *10*: thermopile; *1*, *2*, *4*, *5*: parts of the heat sink.

thermal environment. Therefore one resistance element is needed to measure the temperature of the receiver and one to measure that of the thermal environment. AC and DC bridge techniques are applied for the comparison, the most common employing Wheatstone bridge configurations. The second resistance element should be physically close to the radiation-measuring element to compensate for convective disturbances, pressure fluctuations, changes in temperature of the housing, and instabilities in the bridge supply. The resistors are preferably made of metal wires or films of nickel, platinum, or gold [65Ble]. Thermistors are also used which have a larger temperature coefficient of the resistance. At lower operation temperatures the signal-to-noise ratio of bolometers can be increased considerably [82Mat, 87McD].

Pyroelectric detectors produce a current proportional to the rate of temperature change. The detection mechanism is based on the temperature dependence of the electrical polarization in ferroelectric crystals. Since pyroelectric detectors respond to modulated radiant power only, their use in laser radiometers for measuring cw radiation requires chopping of the incident beam. This can provide considerable drift immunity and allows for the use of drift-free AC amplification techniques [70Put, 75Tif].

Beside the thermal detectors also photoelectric devices or quantum detectors are used in laser radiometry. Photoelectric detectors for laser radiometric applications are either photoconductors or photodiodes. In a photoconductor made of a thin film of a semiconductor material the incident radiation generates additional carriers. These intrinsic band-to-band transitions or extrinsic transitions involving forbidden-gap energy levels result in an increase of conductivity [81Sze]. For sensitive infrared detection, the photoconductor must be cooled in order to reduce thermal ionization of the energy levels. In photodiodes the carriers are mainly generated in the depletion layer of the diode junction. The electron-hole pairs separated by an internal or external electric field recombine by driving an external current. Photodiodes are operated in two different modes: In the photovoltaic mode no bias voltage is applied and the photodiode can be considered as current source. In contrast, in the reverse-bias mode the photocurrent generates a voltage drop at an external load resistance which is used as measuring quantity. The reverse-bias mode is preferred for the detection of pulsed laser radiation.

A practical example of a radiometer for *cw laser radiation* is shown in Fig. 2.1.3. It measures radiant power in the range from 1 mW to 10 W, whereas the lower limit is set by detector and amplifier noise and the upper by the load limit of the electrical heater [89Moe]. The radiation absorber is a polished hollow cone electro-plated with a nearly specular reflecting black nickel layer. The temperature difference between the absorber cone and the heat sink is measured by a thermopile. The electric heater for moderate-accuracy in-situ calibrations of the instrument is wound around the cone. Another design of a thermopile-type radiometer with an integral alignment module can be found in [88Ino]. Further similar systems are described in [77Gun, 91Rad]. A commercial version of a laser radiometer based on a pyroelectric lithium tantalate crystal is described in [89Hen]. For higher radiant power levels of up to 1 kW cavity absorbers cooled by a surrounding jacket of flowing water are employed. The difference in temperature between the outflowing and inflowing water is measured and serves as quantity for the absorbed laser radiant power [96Bra]. A special design of the surface geometry of the cavity reduces the irradiance of the laser beam, thus improving the protection from damaging the surface.

The preferred instruments for *pulsed laser radiation* are thermally absorbing devices such as calorimeters. The receiver element is often a glass-disk, where the radiation is absorbed in the volume instead of on the surface. The absorptance exhibits an excellent stability under chemical and mechanical stress. This type of calorimeter is described in [70Edw, 74Gun]. The radiative load can be reduced by using glass with a low absorption coefficient which increases the length of the absorption path. On the other hand the heat capacity increases linearly with the thickness of the glass-disk which, in conjunction with the poor thermal conductivity of glass, results in long response and cooling times of these detectors. The radiometric scale for laser radiant energy is usually derived from the scale for cw laser radiant power. In [91Moe] a fast electromechanical shutter is used to produce pulses of known laser radiant energy of up to 5 J. The influence of the pulse duration has to be corrected in the calibration procedure. A laser energy meter not depending on a cw laser radiant power scale is described in [90Yua]. In this instrument the light pressure of the laser beam sensed by two mirrors is converted by a moving coil to an electrical signal. The main advantages of this system are fast response and no interruption of the laser beam. The device has been investigated for single laser pulses of radiant energies between 10 mJ and 6 J. Another method not interrupting the laser beam is the photoacoustic calorimetry [86Kim]. There, the radiant energy incident upon a mirror is absorbed at the mirror surface. The absorbed energy generates elastic strain waves which propagate through the mirror substrate. The strain waves eventually pass through a piezoelectric transducer attached to the back of the mirror substrate. The voltage of the piezoelectric crystal gives a direct indication of the amount of energy absorbed at the mirror surface. Since a priori the absorptance of the mirror is not known the instrument has to be calibrated against a standard energy meter.

2.1.4 Outlook – State of the art and trends

Although optical radiometry has been developed for 100 years, measurements of the various radiometric quantities only recently have achieved the required small uncertainties. Today the most accurate detector-based primary radiometric standard is the electrically calibrated cryogenic radiometer. In this instrument the radiant power of – preferably – a laser beam is measured by substituting the absorbed optical power of the laser beam by the electrical power of a heating system. Cryogenic radiometers operate at liquid helium temperatures and have a measurement uncertainty of a few parts in 10^4, a significant improvement over earlier room-temperature radiometers.

Accurate characterization of laser sources is crucial to the effective development and use of industrial technologies such as light-wave telecommunications, laser-based medical instrumentation, materials processing, photolithography, data storage, and laser safety equipment. Traceable measurement standards are essential both for users to have confidence in their measurements and to support quality assurance in the manufacture of lasers and laser systems. Because lasers present a potential safety hazard, it is also important to have measurement standards to satisfy nationally and internationally agreed safety limits. The traceability for laser radiometric measurements in Germany is maintained by the Physikalisch-Technische Bundesanstalt. It meets the requirements for calibration and testing laboratories, certification and accreditation bodies defined in the ISO/IEC Guide 17025 and the DIN/EN 45000 and DIN/EN/ISO 9000 series of standards, see `http://www.ptb.de/en/org/q/q3/q33/_index.htm`.