Chapter 2
Radiation Sources in Radiometric Applications

Abstract This chapter deals with basic features of thermal light sources exploited for radiometric applications in the infrared, visible, and near UV spectral range $\lambda > 250$ nm. The calculation techniques of spectral radiant power and spectral photon flux in different units are also considered for the case of tungsten ribbon filament strip lamps. Quartz tungsten–halogen lamps and deuterium gas-discharge light sources are treated herein as radiation sources for the near UV and vacuum UV spectral range. Also principle characteristics of synchrotron radiation sources are discussed in the context of absolute radiation standards and methods of absolute calibration applied to radiation sources and photodetectors based on this type of radiation.

2.1 General

Some present-day light radiation and temperature standards have been considered in the previous chapter. The radiation sources applicable for spectral sensitivity measurements of spectral devices in wide spectral range from the VUV to IR spectral ranges, which can be used in common scientific, nonmetrological, laboratory will be interested first in this chapter. The sources can be subdivided into two classes: incandescent lamps (filament lamps, namely, tungsten ribbon filament strip lamps, see Sect. 1.1) and calibrated quartz tungsten–halogen lamps. It is the latter class of spectral lamps that provides for working standards of radiation spectra. Such lamps are produced and calibrated by various manufacturers.

2.2 Calibrated Sources of Thermal Radiation

Of *light sources* emitted by incandescent media, the black body is the best source of *thermal radiation*, because for the given temperature its surface element emits the most luminous energy. The spectral radiant emittance of

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nonpolarized radiation $M_e^0(\lambda, T)$ emitted by the black body follows the *Planck's law* [1–3]:

$$M_e^0(\lambda, T) = c_1\lambda^{-5}\left[\exp(c_2/\lambda T) - 1\right]^{-1}, \quad (2.1)$$

where $M_e^0(\lambda, T)$ is expressed in W/m^3; $c_1 = 2\pi hc^2 = (3.7417749 \pm 0.0000022) \times 10^{-16}$ W m^2 is the first radiation constant and $c_2 = hc/k = (1.438769 \pm 0.000012) \times 10^{-2}$ K m is the second radiation constant; c is the light velocity in vacuum; $k = 1.3806505 \times 10^{-23}$ J/K $= 8.617343 \times 10^{-5}$ eV/K is the Boltzmann constant, and h is the Planck's constant. The expression in the *brackets* in (2.1) is the so-called *dimensionless Planck's law*, which can be expressed in terms of spectral radiance $L_e(\lambda)$ [W/(sr m^3)] propagating normal to the surface:

$$L_e^0(\lambda, T) = c_1\lambda^{-5}\left[\exp(c_2/\lambda T) - 1\right]^{-1} \ \ \mathrm{W/(sr\ m^2\ m)}. \quad (2.2)$$

Light sources like those shown in Fig. 1.1 are very bulk and expensive. Moreover, such a source has too low temperature to be suitable for applications required sufficient emitted irradiance in a short-wave spectral range (see Fig. 2.1).

As mentioned above, the strip lamps and quartz tungsten–halogen lamps are commonly used in scientific laboratories. Brightness and color temperatures of the former (see below) and spectra of the latter can be measured in metrological laboratories. The radiance spectrum of a tungsten ribbon filament strip lamp can be determined with a high precision. Now, features of the lamps of this kind will be discussed in detail.

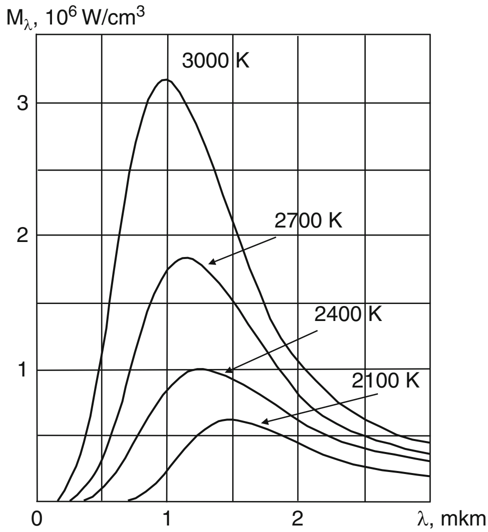

Fig. 2.1 Black body radiation at different temperatures

2.2.1 Planck's Law in Different Units

The measuring system involving *monochromator* and *photodetector* is commonly used for detecting radiation spectra. The *photocurrent* of the photodetector is directly proportional to the photon flux incident on the *photocathode*, but not to the energy flux. In turn, the photon flux is proportional to the *entrance slit* width of the monochromator. The slit width can be expressed in terms of wavelengths. Therefore, the *Planck's curve* should be expressed in suitable spectral units, in wavelengths in this case. Generally, in metrological laboratories, photodetectors are calibrated in energetic units. Finally, sometimes a wavenumber, instead of wavelength, is exploited to calibrate spectral devices. The Planck's law expressed in different units is treated below (see [1–3]).

The spectral radiance, i.e., the energy per unit time, per unit solid angle, per unit surface area, and per unit wavelength interval is expressed to be as follows:

$$L_{\mathrm{e}}^{0}(\lambda, T) = 2\pi hc^{2}\lambda^{-5}\,[\exp(hc/k\lambda T) - 1]^{-1}, \tag{2.3}$$

its physical dimension is W/(sr m^3).

The spectral photon radiance in photonic units, i.e., as the number of photons per unit time, per unit solid angle, per unit surface area, and per unit wavelength interval is given by the formula:

$$L_{h\nu}^{0}(\lambda, T) = 2\pi c\lambda^{-4}\,[\exp(hc/k\lambda T) - 1]^{-1}, \tag{2.4}$$

it is expressed in photon/(s sr m^3).

The energy per unit time, per unit solid angle, per unit surface area, and per unit frequency is as follows:

$$L_{\mathrm{e}}^{0}(\nu, T) = \frac{2\pi h}{c^{2}}\nu^{3}\,[\exp(h\nu/kT) - 1]^{-1}, \tag{2.5}$$

its physical dimension is W/(sr m^2 Hz).

The photon flux per unit time, per unit solid angle, per unit surface area and per unit frequency is found to be as follows:

$$L_{h\nu}^{0}(\nu, T) = \frac{2\pi}{c^{2}}\nu^{2}\,[\exp(h\nu/kT) - 1]^{-1}, \tag{2.6}$$

its unit is photon/(s sr m^2 Hz).

The energy per unit time, per solid angle, per unit surface area, and per unit wavenumber is expressed to be as follows:

$$L_{\mathrm{e}}^{0}(\tilde{\nu}, T) = 2\pi hc^{2}\tilde{\nu}^{3}\,[\exp(hc\tilde{\nu}/kT) - 1]^{-1}, \tag{2.7}$$

its physical dimension is W/(sr m).

The photon flux per unit time, per solid angle, per unit surface area, and per unit wavenumber is found to be as follows:

$$L^0_{h\nu}(\tilde{\nu}, T) = 2\pi c\tilde{\nu}^2\left(e^{hc\tilde{\nu}/kT} - 1\right)^{-1}, \qquad (2.8)$$

it is expressed in photon/(s sr m).

When providing calibration in some *arbitrary* units, the Planck's law should be also expressed in terms of the arbitrary units. It will be noted that the expression in brackets has no physical dimension, whereas the factor with variables λ, ν, $\tilde{\nu}$ has its exponent running from -2 to -5.

2.2.2 Radiation from True Bodies

In fact, thermal radiation is subject to the *Kirchhoff's law* [4], which states that at *thermal equilibrium*, the *absorptivity* (*absorptance*) of a body (or surface) $\alpha(\lambda, T)$ equals its *emissivity* $\varepsilon(\lambda, T)$ for the given wavelength λ and temperature T:

$$\alpha(\lambda, T) = \varepsilon(\lambda, T). \qquad (2.9)$$

Here,

- Absorptance is ratio of radiant power absorbed to radiant power incident on the body surface
- Emissivity is ratio of radiant power emitted by emitted area of the body to radiant power emitted by a *black body* area

It follows from (2.9) that:

- With a black body the absorptance is equal to unity for every wavelength and temperature.
- For a given temperature and wavelength, the emissivity of a true luminous body is always less than that of the black body, because the $\varepsilon(\lambda, T) = \alpha(\lambda, T)$ is less than unity for every true luminous body.

In the practically important case, where $\alpha(\lambda, T) = \text{const}$ and $\alpha(\lambda, T) < 1$, the thermal emissivity of such a surface always obeys the condition: $\varepsilon(\lambda, T) \leq 1$. The surfaces having such features are called *gray surface*, in turn, the body is called *gray body*. A metal surface heated to a high temperature can show features of gray body. In the event, where $\alpha(\lambda, T) = f(\lambda)$, the emitting surface is called a *selective radiator*. All radiating surfaces are selective in a wide spectrum range. In the event of a flat radiating surface, i.e., in the absence of multiple reflections, for the given temperature and for every surface material the *absorptance* and *emissivity* can be found experimentally. The obtained data can be applied for every material used in radiator fabrication. In fact, obtained data of absorptance and emissivity of tungsten are most essential (see Table 2.1), because tungsten is commonly used for production of incandescent lamps (Fig. 2.2).

Table 2.1 The emissivity of well-defined tungsten ribbon as a function of wavelength at different temperatures, *T* varies from 1,800 to 2,800 K [3, 5]

	T (K)					
λ (nm)	1,800	2,000	2,200	2,400	2,600	2,800
230	0.382	0.375	0.368	0.362	0.356	0.348
250	0.442	0.435	0.429	0.424	0.418	0.411
275	0.471	0.466	0.461	0.455	0.450	0.445
300	0.477	0.474	0.471	0.468	0.465	0.456
325	0.477	0.474	0.471	0.468	0.465	0.457
350	0.476	0.473	0.470	0.467	0.464	0.461
375	0.475	0.472	0.469	0.466	0.463	0.463
400	0.473	0.470	0.467	0.464	0.461	0.461
425	0.472	0.468	0.465	0.462	0.458	0.458
450	0.469	0.466	0.462	0.459	0.456	0.454
475	0.466	0.462	0.459	0.455	0.452	0.450
500	0.462	0.459	0.455	0.450	0.447	0.448
525	0.458	0.454	0.450	0.446	0.442	0.446
550	0.454	0.450	0.445	0.441	0.436	0.443
575	0.450	0.445	0.441	0.436	0.431	0.439
600	0.446	0.441	0.436	0.431	0.426	0.434
625	0.443	0.438	0.433	0.428	0.423	0.431
650	0.439	0.434	0.429	0.424	0.419	0.427
656	0.438	0.433	0.428	0.423	0.418	0.426
675	0.435	0.430	0.425	0.420	0.415	0.424
700	0.431	0.426	0.421	0.416	0.411	0.419
725	0.427	0.422	0.417	0.412	0.406	0.415
750	0.422	0.418	0.412	0.407	0.402	0.410
800	0.413	0.408	0.404	0.399	0.394	0.400
850	0.404	0.399	0.394	0.390	0.385	0.391
900	0.394	0.390	0.385	0.381	0.376	0.383
950	0.384	0.380	0.376	0.372	0.368	0.375
1,000	0.375	0.371	0.367	0.364	0.360	0.367
1,100	0.356	0.353	0.350	0.347	0.344	0.352
1,200	0.337	0.336	0.334	0.333	0.331	0.337
1,208	0.322	0.322	0.322	0.322	0.322	0.327
1,300	0;318	0.318	0.319	0.319	0.319	0.325
1,400	0.299	0.301	0.302	0.304	0.305	0.313
1,500	0.283	0.285	0.287	0.290	0.292	0.302
1,600	0.268	0.271	0 2?4	0.277	0.280	0.292
1,700	0 253	0.25?	0.262	0.266	0.270	0.283
1,800	0.239	0.245	0.251	0.256	0.262	0.275
1,900	0.226	0.233	0.240	0.247	0.255	0.267
2,000	0.213	0.222	0.231	0.239	0.248	0.259
2,100	0.202	0.212	0.222	0.232	0.242	0.252
2,200	0.192	0.203	0.214	0.225	0.236	0.245
2,300	0.184	0.195	0.207	0.218	0.229	0.239
2,400	0.177	0.188	0.200	0.212	0.223	0.233

(continued)

Table 2.1 (continued)

	T (K)					
λ (nm)	1,800	2,000	2,200	2,400	2,600	2,800
2,500	0.170	0.182	0.194	0.205	0.217	0.229
2,600	0.164	0.176	0.187	0.199	0.211	0.224
2,700	0.158	0.170	0.182	0.193	0.205	0.219
2,800	0.154	0.165	0.177	0.189	0.200	–
2,900	0.150	0.161	0.172	0.184	0.196	–
3,000	0.146	0.157	0.169	0.180	0.191	–
3,200	0.139	0.150	0.162	0.173	0.184	–
3,400	0.134	0.145	0.156	0.167	0.178	–
3,600	0.129	0.140	0.151	0.162	0.173	–
3,800	0.124	0.135	0.146	0.157	0.168	–
4,000	0.119	0.130	0.141	0.152	0.163	–
4,200	0.115	0.126	0.137	0.148	0.159	–
4,400	0.112	0.123	0.134	0.145	0.155	–
4,600	0.111	0.121	0.131	0.142	0.152	–
4,800	0.109	0.119	0.129	0.139	0.149	–
5,000	0.108	0.117	0.127	0.136	0.146	–

Fig. 2.2 Tungsten ribbon filament strip lamp SIRSH 8.5-200 (MELZ, Russia)

The important point is that the total emission of true bodies involves its own emitted radiation and reflected radiation. In the case of nonflat geometry of radiation source, for example, of spiral shape, then one part of radiation leaves the source after a number of reflections. It is clear that the function $\alpha(\lambda, T)$ determined for a flat surface cannot be applied to that even, a *darkening factor* should be taken into account.

2.2.3 The Brightness and Color Temperatures in Measurements with Strip Lamps

Radiation of heated bodies can be described in terms of the so-called *equivalent temperature*, which is assumed to be the black body temperature. The *brightness temperature* T_b is the temperature at which a black body would have to be to duplicate the observed intensity of the gray body. The *color temperature* T_c of a light source is the temperature of a black body that emits light of comparable hue to that of light source [6, 7]. The brightness and color temperature are most frequently used quantities. It is clear that relationships between the true temperature and equivalent one are dependent on the light source material as well as on its true temperature. Such relationships can be found experimentally that has been done many times. Data of measurements were published in articles and monographs (see Fig. 2.3).

In order to estimate the emission spectrum of a strip lamp it should follow the recommendations given below. For example, the strip lamp calibrated in Russian D.I. Mendeleyev Scientific and Research Institute of Metrology gets the state calibration test certificate from the institute, wherein the dependency of brightness temperature on the lamp current is tabulated at $\lambda = 656$ nm (see Table 2.2).

With choosing a required true temperature, the brightness temperature can be found from Fig. 2.3. Further, a suitable value of the current is calculated from the table attached to the certificate. With required units, see (2.2)–(2.7), and for the given temperature, the blackbody spectrum should be calculated. Finally, the black body intensity should be multiplied by the emissivities of tungsten associated with the given wavelengths (see Table 2.1).

We emphasize that the recommendations above are concerned to strip lamps, whereas the lamps having another shape of their heater element, for example, of spiral shape, will have another emissivity factors. Some special features of calibrating will be discussed in the next chapters of this book. Here, it is worth noting that calibrated strip lamps are lower in cost than that of calibrated quartz tungsten–halogen lamps. The first consideration of using strip lamps at lower temperatures is that they are more long-lived. In other words they should be subject to such expensive procedure as recalibration in a longer period than quartz tungsten–halogen lamps. The author exploited a tungsten ribbon filament lamp several hundreds of hours, which has features similar to those shown in Table 2.2 at temperature 2,700 K (the brightness temperature is equal to 2,152°C). The calibration life as recalibration interval of this lamp class decreases dramatically at high temperatures.

2.2.4 Quartz Tungsten–Halogen Lamps

The maximum accessible temperature of a tungsten lamp depends on the filament evaporation rate. The evaporation causes dusting of the lamp window and

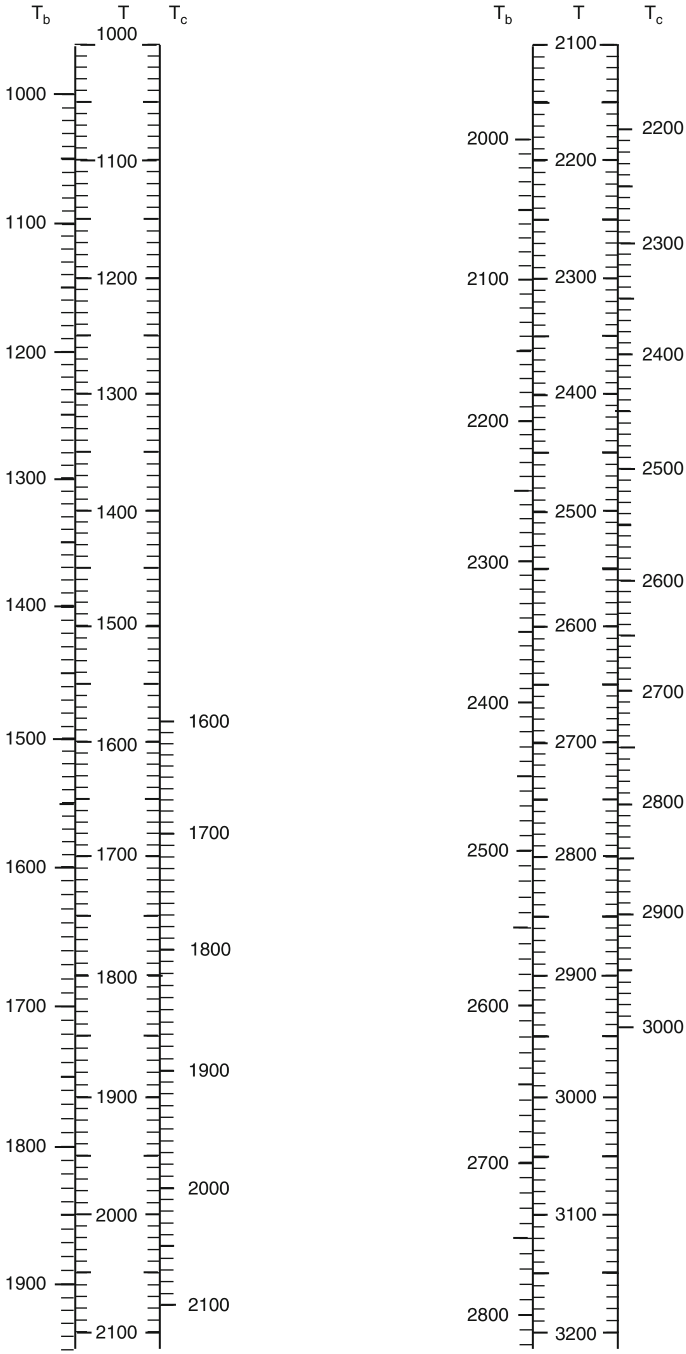

Fig. 2.3 The relationship between the brightness temperature T_b, the true temperature T, and the color temperature T_c in K of a tungsten ribbon lamp [8]

Table 2.2 The brightness temperature as function of the current of a typical SIRSH 8.5-200 tungsten ribbon filament strip lamp

Brightness temperature, t (°C)	1,400	1,500	1,600	1,700	1,800	1,900	2,000	2,100	2,200	2,300
Current (A)	10.76	11.73	12.77	13.88	15.08	16.34	17.68	19.08	20.54	22.04
dI/dt, 10^{-3} A/°C	9.31	10.3	10.76	11.54	12.29	13.01	13.69	14.31	14.84	15.29

Fig. 2.4 The Model 5000-16c 1,000-W FEL lamp [9] (reproduced by permission of Gamma Scientific)

increasing the filament resistance. The addition of halogen such as iodine or bromine to the gas inside the lamp increases the rated life, accessible temperature and light efficiency of the lamp. With high temperature of the lamp bulb, more than 250°C, halogen reacts with atomized tungsten, then resulting product migrate back to the filament, where the very high temperature decomposes it. Bulbs of such lamps are made up of high-quality fused quartz. This results in, among other things, high transmission for the UV radiation. Compared to tungsten strip lamps, the tungsten–halogen lamps (Fig. 2.4) offer the certain advantage due to high temperature. It is because of their high temperature that these lamps make possible to provide calibration up to wavelength 250 nm.

A disadvantage of quartz tungsten–halogen lamps is that there is no way to calculate the emission spectrum, because the lamps have nonstrip shape of their heating element, and there are multiple reflections inside the filament space. Thus for each lamp, the spectrum should be found through measuring, whereas in the case of strip lamps the brightness temperature should only be found. It is of first importance that the lamps call for frequent and expensive recalibrations (in every 50 working hours for the lamps of 200 and 1,000 W). Therefore, when working within the range $\lambda \geq 320$ nm, the author prefers tungsten ribbon filament strip lamps to tungsten–halogen ones. When tungsten–halogen lamps are preferred to be used, it is worth to purchase two specimens, where one of them should be seldom used as a standard for comparison with those that are frequently used. It has been mentioned in Chap. 1 that this recommendation concerns to every type of measuring devices. The quartz tungsten–halogen lamps are produced and calibrated by various manufacturers.

When operating with the both lamp types in a short-wavelength spectrum range, there is a high level of scattered radiation. It leads to huge distinctions in intensity, in several orders, at wavelength from $\lambda \approx 250$ nm to $\lambda \approx 550$ nm for the lamps with halogen cycle and from $\lambda \approx 300$ nm to $\lambda \approx 550$ nm for the strip lamps. In the case of the lamp shown in Fig. 2.4, the distinction is about 1,000 times. Therein lies the answer to the storing of that why calibration of detecting systems in the short-wavelength ranges should be based on special techniques. The techniques will be discussed in Sects. 5.3 and 5.4.

2.3 Gas-Discharge Radiation Sources for the UV of $\lambda > 190$ nm

In the short-wavelength range $\lambda \leq 250$ nm at temperature $T \leq 2{,}900$ K, the weak intensity of black body radiation renders the use of the black body unsuitable for calibration. Otherwise, it would result in serious errors due to the effect of long-wavelength scattered light. Because of this, so-called gas-discharge lamps are the only radiation sources of well-known emission spectra, which are suitable for calibration in the near UV range. The radiation spectrum of the sources can be found, in one way or another, for example, by means of standards based on synchrotron radiation.

Stability of both the spectrum emission and radiating energy is the required feature of any light source. In the case of the gas-discharge lamps, the stability is dictated by *constancy of gas composition* and transparency of the lamp bulb window. By now a wide variety of different light sources of linear and continuous spectrum in the UV and VUV spectral ranges were designed to be applied, in particular, to photochemical research. However, there are available sources of continuous spectrum, which can be used as working facilities for the spectral sensitivity calibration of detection systems. The absolute intensity from such light sources as high-pressure mercury and xenon lamps is very unstable, due to the bulb transparency decreasing in operation. Generally, this disadvantage is characteristic of all the powerful lamps.

At the present time, the gas-discharged deuterium lamps with pressure of a few torrs are the most-used as working standards for spectrum reproduction in the near UV region (Figs. 2.5 and 2.6). The lamps of this kind are produced by various manufacturers [10–14]. The lamps filled with mixtures of deuterium and inert gases, most often with neon, were previously used extensively. Neon was added to bring down the discharge initiation voltage, because with neon Penning ionization occurs, and the electron–ion recombination cross section of neon is far less than

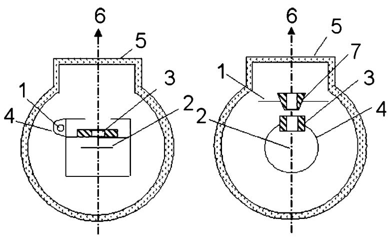

Fig. 2.5 Two representative designs of deuterium lamps in cross sections normal to bulb axis: asymmetric design (the left-hand side); symmetric design (the right-hand side): *1* – cathode, *2* – anode, *3* – discharge pipe, *4* – screen cylinder, *5* – window, *6* – output direction, *7* – anode concentrator [15]

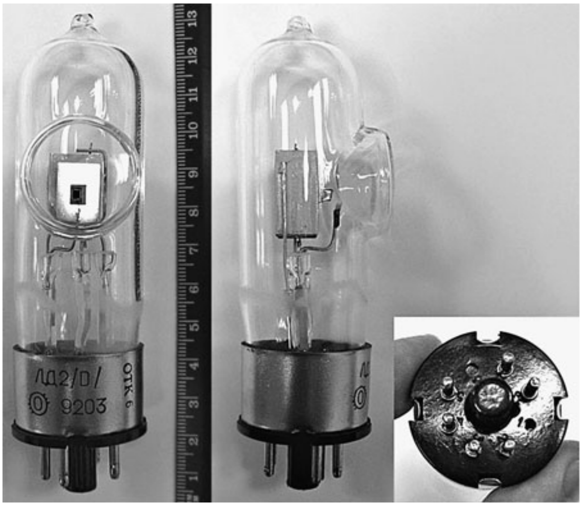

Fig. 2.6 The LD2 (D) deuterium lamp gas-discharge lamp (Russia)

that for hydrogen. Consequently, the concentration of charge particles is higher. Nowadays, deuterium has virtually supplanted hydrogen at all, because of its radiating intensity in the near IR range is 30% greater than that in the event of hydrogen, but in the VUV range it is 10–15% less than that for hydrogen. The operating voltage of such lamps is about 50–80 V, and its current running from 0.3 to 7 A, depending on the lamp power. In his practice, the author tries to avoid extreme operating regimes, which take place at the maximum and minimum permissible value of the lamp current. Operation at a moderate current of the lamp provides more prolonged recalibration period. The discharge initiation voltage of the lamps is found to be between 300 and 500 V, the lamps have falling current–voltage characteristic as of any low pressure discharge process; the lamps are then inoperable without a powerful ballast resistance.

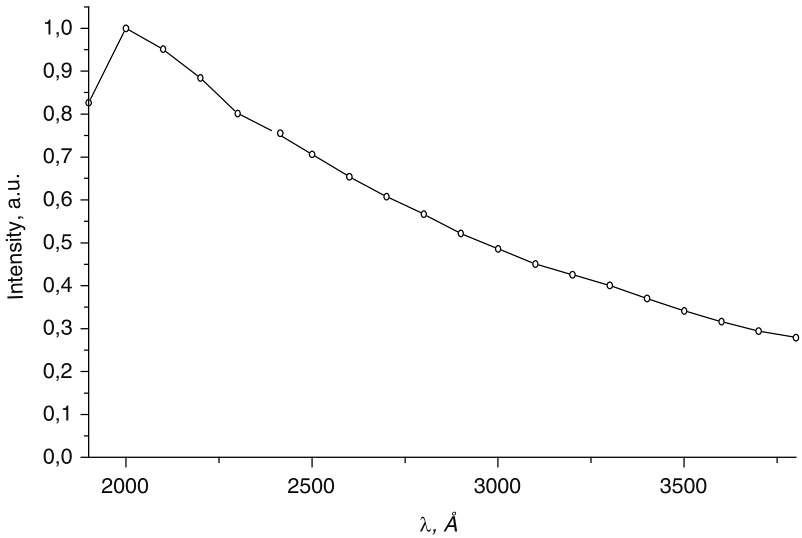

Fig. 2.7 The emission spectrum of the DDS-30 lamp (Russia)

The emission spectrum of the hydrogen and deuterium lamps in the near UV region is a well-known hydrogen continuum $\lambda \geq 380$ nm [16, 17] with the short-wave cutoff due to absorption by the window material (Figs. 2.6 and 2.7). A large body of research has shown the spectrum to be approximately unchanged in a wide range of the lamp current. Hence, if no original transparency of the lamp window loses due to evaporation of the electrodes material and no changes in gas composition occur, one can be sure that the spectrum of the lamp will be unchangeable too. Unfortunately, the lamp windows deteriorate and the gas composition undergoes changes, if for no other reasons than gas emission by internal components of the lamp and decreasing of the deuterium concentration. The lamp intensity decreases and the radiation spectrum changes over time due to several reasons. The internal metal components and coating evaporate, the filament coating material reacts with the window, and the window shadows the lamp output and changes its spectrum due to intense radiation. Therefore, the lamps have need for regular verification, even through the lamps did not used yet. Each lamp, which is scheduled for operation in metrological purposes, should be aged before its calibration procedure, i.e., it should work for 30–80 h in its design mode. It would be a good thing to keep track of the radiation intensity for at least one spectral interval. The lamp will serve for a long time in the event that the observed intensity is virtually unchanged, for example, the relative intensity variations are less than 0.1% for 1 h. Thus this lamp can be calibrated. The calibration life or recalibration interval for deuterium lamps depends on their design, and on external environment. Generally, manufacturers specify 50 operation hours as the calibration life for such lamps. This is not a long period, provided that the preheating period is between 20 and 40 min. In addition, the lamps are assumed to have need for annual recalibration, even though a lamp was not in use.

The anode of the lamp has a small hole, as usual, of diameter 1 mm, which is essentially as the radiation source. Such a design of radiating element of the lamps is generally dictated by that synchrotron radiation is used as a primary standard for calibration. It is assumed synchrotron radiation to be emitted by a point source (see Sect. 2.5). In turn, the small radiating area or "point source" of the lamp is suitable for some applications, and is not well for the other ones. These aspects will be discussed in the next sections in detail.

Ocean Optics [10] and Hamamatsu manufacturer [13] produces xenon lamps of low power 150 W with a quasi-continuous spectrum calibrated in the range 200–800 nm. The recalibration interval of xenon lamps as well as deuterium lamps is assumed to be about 100 h.

2.4 Gas-Discharge Radiation Sources for Vacuum UV of $\lambda > 115$ nm

The operation and basic design of the deuterium lamps used in the VUV range are similar to that have been described in the previous section in detail. The main distinction is the output windows, which usually have plates made up of magnesium fluoride, MgF_2. Second, it is a need to use the vacuum-close joining for the lamp and spectral device [16] (in the so-called vacuum monochromator [17]) (Fig. 2.8).

In the short-wave range, the spectrum of these lamps consists of overlapped lines and bands of atomic and molecular deuterium (Fig. 2.9). Spectra of these lamps were measured many times by using different methods including comparison with synchrotron radiation spectra (see [18–21] and references). Repeatability of the spectra measured in [18] $\lambda = 165$–300 нм spectral range are 8–20% depending on wavelength.

The radiation sources of this type are also assumed to be quasi-point sources, since their emitting areas have diameter about 1 mm. Synchrotron radiation is asserted to be a primary standard for these lamps too. It may be assumed that the recalibration interval for the lamps intended in the vacuum UV range is to be less

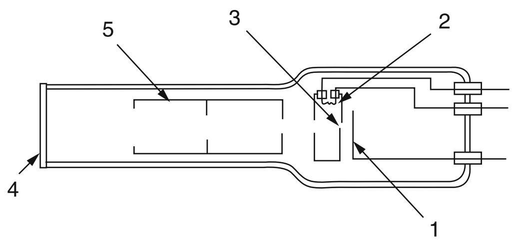

Fig. 2.8 The typical design of deuterium lamps in the vacuum UV range [16]: *1* – anode, *2* – cathode, *3* – emitting area, *4* – MgF_2 window, *5* – antireflection baffles (reproduced by permission of Measurements Science and Technologies, IOP Publishing Ltd)

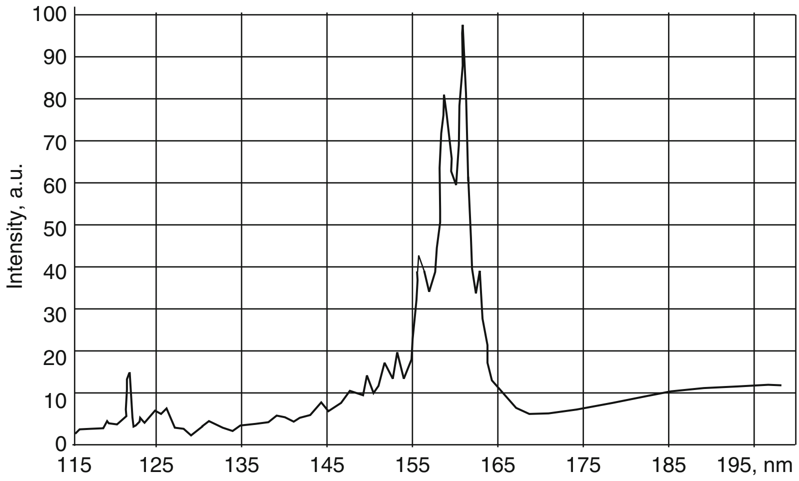

Fig. 2.9 The spectrum of the deuterium lamp of model 632 from McPherson [18] (reproduced by permission of McPherson, Inc.)

than that in the event of the UV range lamps. The first reason is that the so-called F-centers are generated in the fluorite windows, $\lambda \leq 300$ nm, under action of incident radiation of wavelength [19].

2.5 Synchrotron Radiation

Synchrotron radiation (SR) is electromagnetic radiation generated by accelerated charged particle moving near the light velocity through a magnetic field. This may be achieved in the synchrotrons or storage rings. Such artificially produced radiation may range from the IR range to X-rays [20].

Synchrotron radiation is used as an absolute radiation standard, since its characteristics are calculable by the Schwinger equation [21]. In the UV and shorter wavelength, synchrotron radiation emitted from a storage ring has the lowest (about 0.04% [22]) uncertainty in calculable irradiance among all known radiation standards to date. Synchrotron radiation as a primary irradiance standard for a broad spectral range from X-rays to infrared has since been established at several synchrotron facilities around the world in USA, Great Britain, Japan, and Germany (see [22–24] and references).

The characteristics of synchrotron radiation can be accurately determined based on Schwinger's equation, which expresses the radiant power at the wavelength λ, i.e., photon energy emitted from a single relativistic electron with electron energy E deflected in a homogeneous magnetic field of magnetic induction B. The spectral radiant power (see Table 1.1) of synchrotron radiation through an aperture of size $a \times b$ at distance d, thus, may be calculated and expressed in the general form as follows:

$$\Phi_{\mathrm{SR}}(\lambda,\, E_{\mathrm{e}},\, B,\, I,\, \Sigma_y,\, \Psi,\, d,\, a,\, b), \tag{2.10}$$

where I is the electron beam current, Σ_y is the effective vertical source size, and Ψ is the observer's angle above or below the orbital plane defined by the centre of the aperture. The effective vertical source size is derived from the vertical electron beam size σ_y and beam divergence $\sigma_{y'}$ according to [21]:

$$\Sigma_y = \left(\sigma_y^2 + \mathrm{d}^2\sigma_{y'}^2\right)^{1/2}. \tag{2.11}$$

The spectral radiant power emitted by a relativistic charge e into a solid angle dΩ at a wavelength interval of dλ can be written as follows [23, 24]:

$$\frac{\mathrm{d}^2\Phi_{\mathrm{SR}}(\lambda,\, \Omega)}{\mathrm{d}\lambda \mathrm{d}\Omega} = \frac{27e^2}{32\pi^3\rho^2}\left(\frac{\lambda_{\mathrm{c}}}{\lambda}\right)^4 \gamma^8\left(1+\gamma^2\Psi^2\right)^2\left[K_{2/3}^2(z) + \frac{\gamma^2\Psi^2}{1+\gamma^2\Psi^2}K_{1/3}^2(z)\right], \tag{2.12}$$

$$P_0(\lambda, E, R, \Psi) = \frac{27e^2c}{32\pi^3R^3}\left(\frac{\lambda_{\mathrm{c}}}{\lambda}\right)^4 \gamma^8\left[1+(\gamma\Psi)^2\right]^2 K_{3/2}^2(\xi) + \frac{(\gamma\xi)^2}{1+(\gamma\xi)^2}K_{1/3}^2(\xi), \tag{2.13}$$

where ρ is the radius of curvature of the electron's orbit, $K_{2/3}^2(z)$ and $K_{2/3}^2(z)$ are modified Bessel functions, and λ_{c} is the critical wavelength defined as follows:

$$\lambda_{\mathrm{c}} = 4\pi\rho/3\gamma^3,\ \gamma = E_{\mathrm{e}}/m_{\mathrm{e}}c^2, \tag{2.14}$$

where m_{e} is the rest mass of the electron, and c is the light velocity, $m_{\mathrm{e}}c^2 = 0.511$ MeV. The two modified Bessel functions at the right-hand side of (2.12) represent the contributions from horizontal and vertical polarizations, respectively. At $\Psi = 0$, the term for vertical polarization vanishes, and the radiation is linearly polarized in the horizontal direction. In addition, there are the following definitions:

$$K_{2/3}^2(\xi),\ K_{1/2}^2(\xi) \tag{2.15}$$

are the McDonald functions, and

$$z = \frac{\lambda_{\mathrm{c}}}{2\lambda}\left[1 + (\gamma\Psi)^2\right]^{3/2}. \tag{2.16}$$

Synchrotron radiation propagates within a narrow cone localized close to the tangent to the orbit; the radiation is polarized, its polarization can be calculated. The maximum is positioned at the following wavelength:

$$\lambda_{\max} = 0.42\lambda_{\mathrm{c}}, \tag{2.17}$$

Table 2.3 List of PTB beamlines concerning this book at BESSY II, typical applications and photon energy ranges (see [22])

N in Fig. 2.7	Beamline (application)	Photon energy
3a	Undispersed bending magnet radiation (calibration of energy dispersive detector systems)	6 eV to 50 keV
3b	Normal-incidence spectrometer (source calibration)	3–35 eV

Table 2.4 List of MLS beamlines concerning this book, typical applications and wavelength ranges (see [22])

N in Fig. 2.8	Beamline (application)	Wavelengths	Status
1d	UV/VUV monochromator for undulator radiation	4–400 nm	Operational in 2011
2a operational	White-light bending magnet radiation (use of calculable SR)		Operational
2b	UV/VUV spectrometer (source calibration)	7–400 nm	Operational in 2010
4	UV/VUV monochromator (detector calibration, reflectometry)	40–400 nm	Operational
5	THz beamline	0.6 μm to 8 mm	Operational
6	IR beamline	0.6 μm to 8 mm	Operational

which depends upon the electron energy and the radius of curvature of the electron orbit. For the given parameters of the accelerator or storage unit listed above and electron beam density, absolute intensity of spectral lines and polarization in the given direction can be calculated.

Some metrological facilities of synchrotron radiation laboratories, namely, the Physikalisch-Technische Bundesanstalt (PTB) electron storage ring *BESSY II* and *Metrology Light Source* (MLS) are described in Ref. [22]. At the *BESSY II* and MLS the activities have been extended to a broad range of fundamental and applied photon metrology in the range from the far infrared to hard X-rays, including methods like cryogenic radiometry, reflectometry, and X-ray fluorescence spectroscopy. Some applications of the PTB beamlines concerning this book are given in Tables 2.3 and 2.4.

Calculated spectral radiant power of blackbody, MLS and BESSY II radiation sources are shown in Fig. 2.10.

2.5.1 Calibration of Radiation Sources

Radiation sources are calibrated as secondary standards by comparison with the SR primary standard. For this purpose, the radiation of the sources is spectrally dispersed and detected by means of a movable monochromator–detector system that is alternately exposed under analogous conditions as shown in Fig. 2.11.

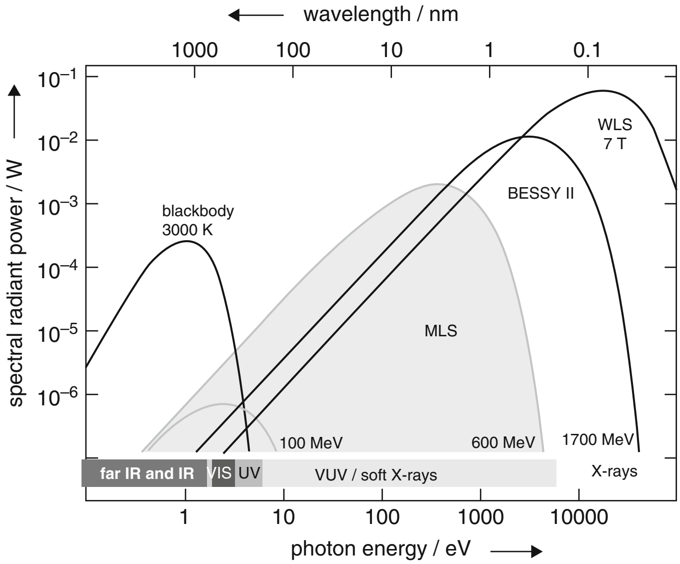

Fig. 2.10 Calculated radiant power of radiation sources into a spectral bandpass of 1% of the photon energy or wavelength and through the aperture of 10 mm radius: blackbody radiator ($T = 3{,}000$ K), MLS (the electron energy 100 and 600 MeV), and BESSY II [the electron energy 1.7 GeV; the bending magnetic field 1.3 and 7 T (WLS)] (see [22] for details) [reproduced by permission of Physica Status Solidi (B)]

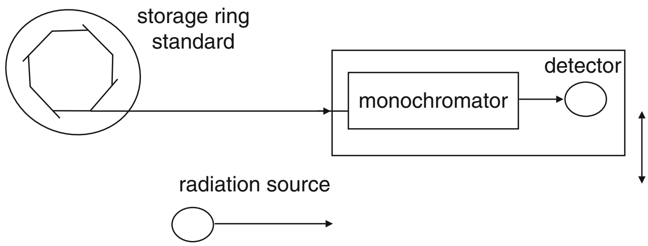

Fig. 2.11 Calibration of radiation sources using the electron storage ring as a primary radiation source standard [22] [reproduced by permission of Physica Status Solidi (B)]

PTB's source calibration capabilities based on calculable SR currently cover the UV and VUV wavelength range from 400 to 40 nm at BESSY II (beamline 3b in Table 2.3) and will be extended down to 7 nm at the MLS (beamline 2b in Table 2.4). The calibration refers to the measurement of spectral radiant intensity $J_e(\lambda)$ and spectral radiance $L_e(\lambda)$ (see Table 1.1) of quasi-point sources with a source area in the order of 1 mm^2.

$$J_e(\lambda) = \Phi_e(\lambda)/\Delta\Omega \text{ and } L_e(\lambda) = \Phi_e(\lambda)/\Delta\Omega\Delta A. \tag{2.18}$$

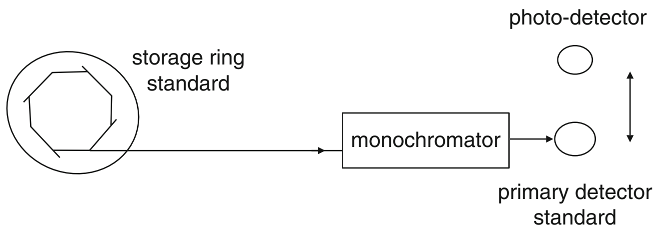

Fig. 2.12 Photodetector calibration by the use of a primary detector standard [22] [reproduced by permission of Physica Status Solidi (B)]

In both cases, the spectral radiant power $\Phi_e(\lambda)$ of the source is obtained by comparing with the calculable SR. The solid acceptance angle $\Delta\Omega$ is defined through an aperture of well-known size and position with respect to the point source. In addition, the accepted part ΔA of the source area is confined and defined by the monochromator entrance aperture which is located in the image plane of the premirror being part of the beamline. In the case of radiant intensity calibrations and SR measurements, the entrance aperture is to be larger than the image of the source.

With deuterium lamps as secondary source standards in the UV and vacuum UV spectral range $\lambda \approx 115$–400 nm, relative calibration standard uncertainties for spectral radiance are as follows: 5, 18, 5, 3.5 and 2.5% in the spectral ranges $\lambda = 115$–120.5, 120.5–122.5, 122.5–165, 165–175 and 175–400 nm, respectively.

2.5.2 Calibration of Photodetectors

In cases where dispersed radiation is required to perform calibrations, the calculability of SR with its broad continuous spectrum cannot be applied. Here, the radiant power of spectrally dispersed SR behind a monochromator is measured in absolute terms by means of a primary detector standard. This allows the output signal of any kind of photodetection system to be calibrated by comparison as shown in Fig. 2.12.

Since the beginning of the 1980s, electrically calibrated substitution radiometers (ESRs) operated at cryogenic temperatures have been used as primary detector standards, initially used for optical radiation only.

These radiometers are thermal detectors based on the equivalence of electrical and radiant heating of a cavity absorber. They are based on the use of a cavity absorber at nearly liquid helium temperature (see [25, 26]).

Problems

1. Based on formulae Sect. 1.2 and formula (2.3), derive the formulae from (2.4) to (2.8).
2. For the given brightness temperature 2,147°C calculate the emission spectrum of a tungsten ribbon filament strip lamp in photon units, in photon/(s sr m^2 nm)

units, at the wavelength interval 5 nm and interval 300–1,000 nm. Estimate the ratio of intensities at $\lambda = 320$ nm and $\lambda = 600$ nm.

3. A radiation source was calibrated in terms of W/(m^2 m sr). Convert the calibration to another units: photon/(s sr m^2 nm).

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