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2000 Metrologia 37 305

(http://iopscience.iop.org/0026-1394/37/4/7)

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T. Kübarsepp, P. Kärhä, F. Manoocheri, S. Nevas, L. Ylianttila and E. Ikonen

Abstract. A method of measuring the absolute spectral irradiance of quartz-halogen-tungsten lamps is described, based on the known responsivity of a filter radiometer, the components of which are separately characterized. The characterization is described for the wide wavelength range essential for deriving the spectrum of a lamp, from 260 nm to 950 nm. Novel methods of interpolation and measurement are implemented for the spectral responsivity of the filter radiometer. The combined standard uncertainty of spectral irradiance measurements is less than 1.4 parts in 10^2 from 290 nm to 320 nm (ultraviolet B) and 4 parts in 10^3 from 440 nm to 900 nm (visible to near-infrared). As an example, the derived spectral irradiances of two lamps measured at the Helsinki University of Technology (HUT, Finland) are presented and compared with the measurement results of the National Institute of Standards and Technology (NIST, USA) and the Physikalisch-Technische Bundesanstalt (PTB, Germany). The comparisons indicate that the HUT spectral irradiance scale is between those of the NIST and the PTB in the wavelength range 290 nm to 900 nm. The long-term reproducibility of the spectral irradiance measurements is also presented. Over a period of two years, the reproducibility appears to be better than 1 part in 10^2.

1. Introduction

Detector-based facilities for absolute measurements of optical quantities have proved to be accurate and reproducible. When using a cryogenic radiometer to realize the unit of optical radiant power, the watt, a relative uncertainty of almost 10^{-5} is approached [1]. Using detector-based technology, improvements in the realization of units of other optical quantities related to the visible wavelength range, such as illuminance, luminous intensity and spectral irradiance, have recently been obtained [2-7].

Two comparison measurements of spectral irradiance scales were organized by the Consultative Committee for Photometry and Radiometry (CCPR) in 1990 and 1996. Both comparisons showed differences between the scales of national standards laboratories of ±4 % in the near-ultraviolet (near-UV) and ±1 % in the visible and near-infrared (VIS-NIR) wavelength ranges [8, 9]. The need for further work to reduce the differences between the scales was pointed out.

Kärhä et al. [4] have described a suitable method based on a compact filter radiometer, which can be used for accurate measurements of absolute spectral irradiance. This method has been successfully used in the VIS-NIR [4] and the near-UV wavelengths [10]. The combined standard uncertainties quoted are less than 5 parts in 10^3 for the VIS-NIR and 1.4 parts in 10^2 for the near-UV.

In this report, we describe a method of measuring spectral irradiance in the wide wavelength interval from 290 nm to 900 nm. A filter radiometer based on a silicon trap detector is used. A thorough characterization of the components of the filter radiometer is presented. The uncertainty sources arising from each component are studied in detail; since our earlier publications on the subject, several improvements have been made to reach low uncertainties in the UV range. In order to evaluate the applicability of the method, we have measured the spectral irradiance of several 1 kW FEL-type lamps. Three of the lamps have been involved in a direct comparison measurement organized by the PTB, and the others are directly traceable to the NIST. The spectral irradiance values determined at the HUT are presented and compared with those of the NIST and the PTB. We have also studied the reproducibility of our method by regularly measuring a seasoned FEL-type lamp. The results over a period of two years are presented.

2. Measurement method

The HUT method of measuring absolute spectral irradiance is based on a filter radiometer whose components are characterized separately. The filter

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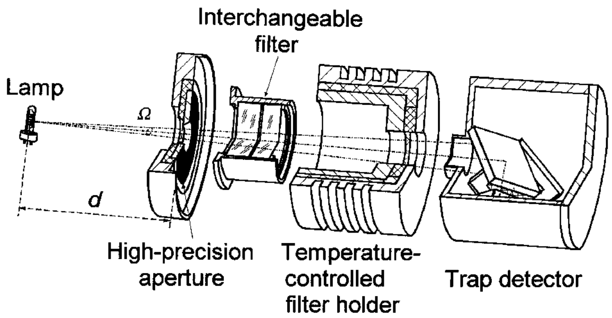

Figure 1. Schematic layout of the components in the measurement of absolute spectral irradiance using a filter radiometer. d: distance; Ω: solid angle.

radiometer is composed of a trap detector, a set of temperature-controlled bandpass interference filters and a high-precision aperture (Figure 1). The trap detector consists of three photodiodes arranged in such a way that light can emerge from the detector only after multiple reflections. In the measurements, the filter radiometer is placed at a given distance, d, from the filament of the lamp. The output current of the filter radiometer is recorded at several wavelengths, which are selected from the continuous spectrum of the lamp using a set of bandpass filters. The filters are mounted in special holders to allow fast and reliable changes. A detailed description of the construction of the filter radiometer may be found in [11], therefore we concentrate on the description of the characterization of the individual components of the device.

2.1 Trap detector

The absolute spectral responsivity of the polarization-independent reflection trap detector [12] is determined in two steps. In the first stage, the absolute responsivity is measured using a cryogenic radiometer [13] at a few visible laser wavelengths. The reflectance of the trap detector is measured at the same laser wavelengths. Reflectance values calculated with Fresnel equations are fitted to the measured reflectance values, giving the effective value of the thickness of the antireflection coating [14]. Using the calculated reflectance values and the model for internal quantum efficiency developed by Gentile et al. [15], the responsivity is determined at wavelengths other than those measured. As a result, the responsivity is obtained at any wavelength in the spectral range 360 nm to 950 nm.

In the second stage, the responsivity of the trap detector is measured using a pyroelectric radiometer [16] in the wavelength range 260 nm to 400 nm. A set-up including a high-accuracy spectrometer [17] is used in the measurements. The responsivity of the pyroelectric radiometer is assumed to be flat within ± 0.5 %, as specified by the manufacturer.

In the near-UV, a new model is used for the interpolation of the responsivity [18]. In our interpolation method, the effect of the quantum yield of silicon is taken into account. This results in the first extension into the near-UV of the model for internal quantum efficiency developed by Gentile et al. [15]. The interpolation function is based on semiconductor physics and it reproduces the structure of the responsivity of silicon photodetectors below 400 nm. This is an improvement compared with a simple spline interpolation, which does not take into account the physical reasons for the structure. Using our model, the responsivity values can be interpolated with a standard deviation of 4 parts in 10^3 in the wavelength range 260 nm to 400 nm. The standard deviation is close to the assumed flatness of the pyroelectric radiometer.

The stability of the responsivity of a trap detector is excellent, unless dust particles or other contamination enter the device. We have measured the stability of our trap detector over one year and found it to be better than 2 parts in 10^3 in the near-UV wavelength interval, and better than 7 parts in 10^4 in the VIS-NIR wavelength interval.

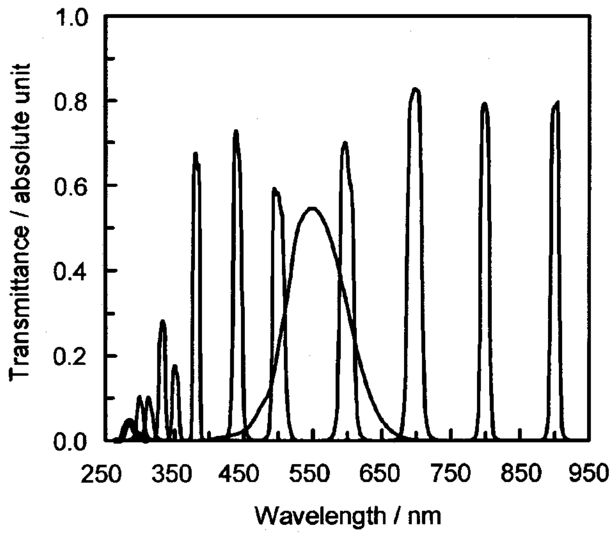

Figure 2. Transmittance curves of the thirteen filters used in the measurement of spectral irradiance at the HUT.

2.2 Filters

We currently use thirteen filters (Figure 2) for measurements of spectral irradiance. The peak wavelengths of the filters are between 285 nm and 900 nm. The full widths at half maximum (FWHM) of the narrow-bandpass interference filters range from 10 nm to 20 nm. An additional broadband filter is used to match the responsivity of the filter radiometer to the spectral luminous efficiency function, $V(\lambda)$, for photopic vision. Realization of photometric units using this filter radiometer is described in [19]. For the VIS-NIR wavelength range, it is enough to have filters with peak wavelengths separated from each other by approximately 100 nm. In the near-UV, however, the

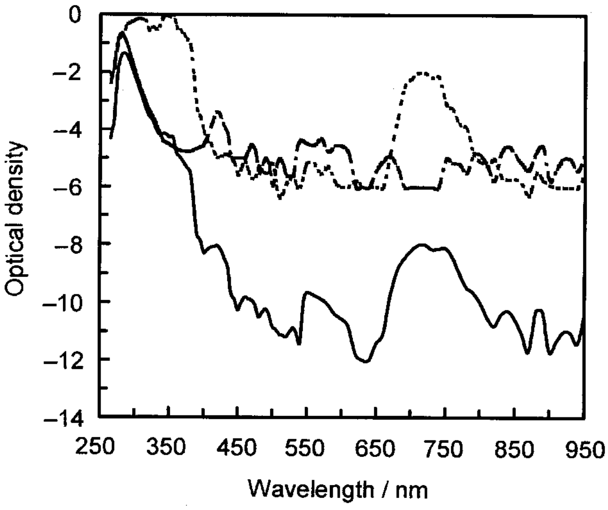

Figure 3. Transmittance of the 285 nm filter (solid curve) as a combination of transmittances of a 280 nm narrowband filter (dot-dashed curve) and a blocking filter (dotted curve) depicted in the scale of optical density.

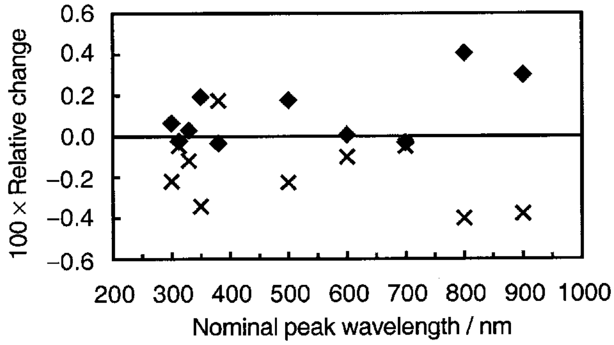

Figure 4. Measured relative changes in the signal of the filter radiometer at different filter temperatures (♦ 18 °C; × 32 °C). The filters measured are used for the realization of the spectral irradiance scale at the HUT. The measured signal is normalized to that obtained at 25 °C.

separation between the central wavelengths of the filters should be much smaller. This is important when measuring light sources whose radiation output drops steeply at near-UV wavelengths (e.g. quartz-halogen-tungsten lamps).

All UV bandpass filters are combined with an additional blocking glass filter (Oriel 51124 Visible Absorbing Filter) in order to suppress out-of-band leakage to the level of 10^{-8} at VIS-NIR wavelengths. The visible-absorbing filter is mounted between the detector and the interference filter to reduce the effects of heat from the light source.

The transmittances of the filters are measured using a high-accuracy reference spectrometer [20]. All combined UV filters are characterized in two steps. First, the transmittances of the blocking filters and the interference filters are measured separately in order to obtain reliable out-of-band transmittance data in the VIS-NIR. Second, the filters are stacked together, leaving an air-gap between them to reduce the effects of interference, and the transmittance of the filter package is measured within the passband. Finally, the results of both measurements are linked in order to cover the entire wavelength range from 260 nm to 950 nm. Figure 3 shows an example of the measurement results obtained with the combined filter, which has a peak wavelength at 285 nm. The measured transmittances of the narrowband filter and the blocking filter are also shown separately. With this cascading measurement method, transmittance data with a resolution of 10^{-8} and below can be obtained. This is not possible by a single measurement with our reference spectrometer, as its maximum resolution is of the order of 10^{-6}.

During the transmittance measurements the temperature of the filters is stabilized to (25 ± 0.2) °C by a temperature-controlled filter holder. The same temperature is used in the measurement of light sources. The change in temperature causes changes in both the effective wavelength and the maximum value of transmittance of the filters. Fluctuations in the temperature of the filters thus have an effect on the accuracy of the lamp measurement. We have studied the magnitude of such an effect by determining the change in the output signal of the filter radiometer when the temperature of the filters is changed by ± 7 °C from the normally used value of 25 °C. Figure 4 presents the results: for some filters the relative temperature coefficients of the signals are as large as 4 parts in 10^3 for a temperature change of 7 °C. This suggests that, when a high level of accuracy is required, large temperature changes of the filters should be avoided in both transmittance and spectral irradiance measurements.

Another key issue is the ageing of the filters: not only the value of the peak transmittance but also the shape of the spectral transmittance curve can change. For UV filters with peak transmittances at 285 nm, 300 nm, 313 nm and 330 nm, we have measured changes in the integrated transmittance values of $+2$ parts in 10^2, -4 parts in 10^3, $+5$ parts in 10^3 and -1 part in 10^2, respectively, over a period of ten months. For some filters, sudden changes in transmittance can be detected visually: the edges gradually become fogged, shrinking the active area of the filter. This is probably caused by penetration of moisture (e.g. water vapour) between the layers through imperfect sealing. The effect could continue for several months, until the whole area of the filter is covered, rendering it useless and in need of replacement. We conclude that the transmittance of our current filters should be measured every six months, unless earlier visual inspection reveals any damage on the filter surfaces.

2.3 Aperture

An aperture with a nominal inner diameter of 3 mm is used in the measurements. The area of the aperture

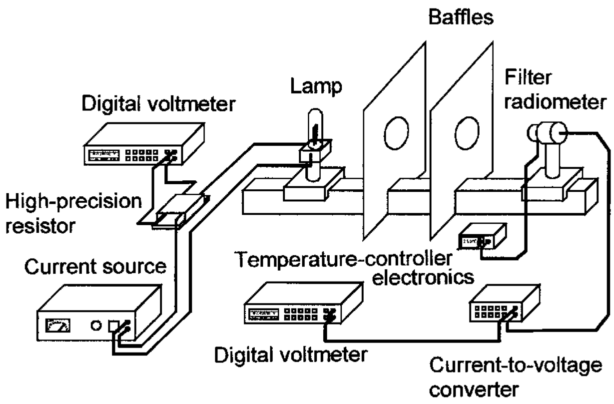

Figure 5. Schematic diagram of the set-up for measurements of spectral irradiance of lamps [10].

is measured by the direct optical method developed at the HUT [21]. At a measurement distance of 0.5 m, the use of an aperture with larger diameter would result in signal loss owing to overfilling of the photodiodes in our trap detector by the divergent light beam from the lamp (for detailed discussion see, for example, [22]).

2.4 Measurement set-up

The filter radiometer described is used to measure the spectral irradiance of quartz-halogen-tungsten lamps. Figure 5 shows the measurement set-up. The lamp under test and the filter radiometer are mounted on an optical rail and aligned on the optical axis using an alignment laser [23]. The distance between the filament of the lamp and the plane of the high-precision aperture of the filter radiometer is adjusted to the desired value using a magneto-mechanical distance measurement unit, unless otherwise stated. Normally, two baffles are used to reduce the effect of scattered light. During the measurements the filter radiometer is irradiated for short periods only, in order to minimize the ageing of the filters due to UV light.

The lamps are operated in constant-current mode. The value of the current is monitored as a voltage drop across a high-precision resistor.

The output signal of the filter radiometer is measured by a current-to-voltage converter and a digital voltmeter. The current-to-voltage converter is needed to avoid electrical loading of the filter radiometer by the current measurement.

2.5 Determination of spectral irradiance

The method for determining spectral irradiance is based on a modified Planck's radiation law:

$$E_c(\lambda) = \frac{Bc_1\varepsilon'(\lambda)}{\lambda^5\left[\exp\left(\frac{c_2}{\lambda T}\right) - 1\right]}, \tag{1}$$

where λ is the radiation wavelength in air, $c_1 \equiv 2\pi c^2 h = 3.7418\times10^{-16}$ J m^{-3} s^{-1} is determined in terms of fundamental constants, B is an auxiliary factor including the effective area of the radiator, $\varepsilon'(\lambda)$ is the effective emissivity of the light source, $c_2 \equiv hc/k = 1.4388\times10^{-2}$ m K is the second radiation constant, and T is the temperature of the filament of the light source in kelvin. The effective emissivity $\varepsilon'(\lambda)$ of the light source comprises the emissivity of the filament material and the transmittance of the glass envelope of the lamp.

During the measurements the output radiation of the lamp passes through the high-precision aperture and the filter referred to with subscript k, and enters the trap detector (Figure 1). The light absorbed in the trap detector generates a photocurrent $i_{\mathrm{m},k}$, whose value is recorded.

The expected photocurrent can be calculated at each measurement wavelength as

$$i_{c,k} = A\int E_c(\lambda)R(\lambda)\tau_k(\lambda)\mathrm{d}\lambda, \tag{2}$$

where A is the area of the high-precision aperture, $R(\lambda)$ is the responsivity of the trap detector, and $\tau_k(\lambda)$ is the transmittance of the k-th filter. In the calculation of $R(\lambda)\tau_k(\lambda)$, we take into account the correction for interreflection between the filter and the trap detector. The correction is larger at UV wavelengths owing to increased back-reflection from the trap detector. A difference function is calculated as

$$\Delta = \sum_{k=1}^{N}\left[\left(\frac{i_{\mathrm{m},k}}{i_{c,k}}\right) - 1\right]^2, \tag{3}$$

where N is the number of the filters used. The difference function is then minimized by optimizing the values of the parameters B and T in (1). The preliminary values of the effective emissivity are then replaced by new values, which are the results of a P-th degree polynomial fitting. The new values are, in turn, used to continue the minimization of the difference function (3) at the effective wavelengths $\lambda_{\mathrm{eff},k}$ of the filter defined as

$$\lambda_{\mathrm{eff},k} = \frac{\int \lambda E_c(\lambda)R(\lambda)\tau_k(\lambda)\mathrm{d}\lambda}{\int E_c(\lambda)R(\lambda)\tau_k(\lambda)\mathrm{d}\lambda}. \tag{4}$$

The iteration method requires preliminary knowledge of the spectrum of the light source. For interpolation of the spectrum of quartz-halogen-tungsten lamps, we have adopted the spectral emissivity data published by De Vos [24] as preliminary values. The spectrum of the tungsten-filament lamp is calculated by separately interpolating the parts of the spectrum in the UV and VIS-NIR wavelength ranges, as suggested in [25]. The separate interpolation yields a minimum difference between the measured and calculated values of spectral irradiance in the UV range, where the emissivity of tungsten has a complex spectral structure.

Table 1. Relative uncertainty components of the spectral irradiance measurements at different wavelengths.

Source of uncertainty	100 × Relative uncertainty												
Effective wavelength/nm	291	302	315	333	352	382	441	501	572	599	698	801	902
Detector responsivity	**0.67**	**0.67**	**0.54**	**0.51**	**0.51**	**0.26**	**0.07**	**0.07**	**0.07**	**0.07**	**0.07**	**0.07**	**0.06**
Cryogenic radiometer	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Reflectance modelling	–	–	–	–	–	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.02
Internal quantum efficiency modelling	–	–	–	–	–	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Spectral flatness of pyroelectric radiometer	0.50	0.50	0.30	0.30	0.30	0.15	–	–	–	–	–	–	–
Repeatability	0.40	0.40	0.40	0.40	0.40	0.20	–	–	–	–	–	–	–
Current measurement	0.20	0.20	0.20	0.10	0.10	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Non-linearity	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Filter transmittance	**0.97**	**0.46**	**0.37**	**0.31**	**0.31**	**0.36**	**0.18**	**0.14**	**0.09**	**0.11**	**0.11**	**0.15**	**0.15**
Peak transmittance	0.89	0.32	0.13	0.19	0.21	0.29	0.12	0.10	0.07	0.07	0.08	0.10	0.09
Wavelength uncertainty	0.24	0.21	0.19	0.16	0.14	0.11	0.08	0.05	0.03	0.03	0.01	0.01	0.01
Wavelength repeatability	0.08	0.12	0.12	0.15	0.14	0.15	0.11	0.08	0.01	0.07	0.07	0.11	0.11
Temperature	0.03	0.03	0.03	0.03	0.03	0.00	0.03	0.01	0.02	0.00	0.00	0.02	0.02
Out-of-band leakage	0.30	0.22	0.26	0.10	0.11	0.08	0.03	0.04	0.03	0.03	0.04	0.05	0.05
Irradiance measurement	**0.11**	**0.11**	**0.11**	**0.14**	**0.14**	**0.11**	**0.11**	**0.11**	**0.11**	**0.11**	**0.11**	**0.11**	**0.11**
Distance measurement (500 mm)	0.04	0.04	0.04	0.09	0.09	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Repeatability	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Diffraction	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Aperture area	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**
Interreflection	**0.26**	**0.14**	**0.10**	**0.10**	**0.11**	**0.11**	**0.03**	**0.02**	**0.02**	**0.02**	**0.01**	**0.01**	**0.01**
Interpolation	**0.57**	**0.27**	**0.27**	**0.27**	**0.27**	**0.27**	**0.27**	**0.27**	**0.27**	**0.27**	**0.27**	**0.27**	**0.27**
Combined standard uncertainty	**1.34**	**0.87**	**0.72**	**0.68**	**0.68**	**0.54**	**0.35**	**0.33**	**0.32**	**0.32**	**0.32**	**0.34**	**0.34**
Expanded uncertainty $(k = 2)$	**2.7**	**1.7**	**1.4**	**1.4**	**1.4**	**1.1**	**0.7**	**0.7**	**0.6**	**0.6**	**0.6**	**0.7**	**0.7**

3. Uncertainty budget

Table 1 shows the detailed uncertainty budget of the measurements of absolute spectral irradiance. All uncertainty components are presented as 1 σ values.

A high level of accuracy in detector responsivity is obtained when the cryogenic radiometer is used at visible wavelengths. The interpolation of the responsivity to wavelengths other than those directly measured induces small uncertainty components. These have been estimated by analysing the sensitivity of the interpolated responsivity to the fitting parameters needed for modelling the reflectance [14] and the internal quantum efficiency [15]. Larger uncertainties at shorter wavelengths mainly arise from transfer of the absolute responsivity scale from the visible to the near-UV spectral range using a pyroelectric radiometer. The uncertainty component arising from current measurement is obtained from the calibration data of the current-to-voltage converter and the multimeter. The estimate of the uncertainty induced by non-linearity is based on the measurement results given in [26].

The uncertainty induced by the filter transmittance measurements includes five components. A model assuming a rectangular shape for the spectral transmittance of the filter was used to evaluate the effects of the first three of these components. The height and width of the rectangle are considered to be equal to the transmittance value at the effective wavelength and to the FWHM of the filter, respectively [6]. The centre of the rectangular transmittance shape is assigned to the effective wavelength. The uncertainty of the transmittance value at λ_{eff} was used to calculate the peak-transmittance uncertainty component. The accuracy of the wavelength scale of the spectrometer has an effect on the value of λ_{eff} obtained in the spectral irradiance measurements. An experimentally determined standard uncertainty of 0.06 nm [20] in the wavelength was used to estimate the effect of a change in the value of λ_{eff} on the measured spectral irradiance value. Wavelength repeatability can change the FWHM ($\Delta\lambda$) of the filter. Using the uncertainty of the wavelength-setting repeatability, $\delta\lambda = 0.015$ nm [20], the given uncertainty component was calculated as $\delta\lambda/\Delta\lambda$. Assuming the uncertainty of the temperature of the filter glass substrate to be 0.2 °C, the uncertainty contribution caused by the temperature variation was calculated based on the measured temperature sensitivity of the filter radiometer (Figure 4). The uncertainty component arising from out-of-band leakage measurements was obtained as a relative contribution to the measured signal, when both components of combined out-of-band transmittance are varied by the resolution of the spectrometer, $\pm 10^{-6}$.

The standard uncertainty in the distance setting at the HUT is 0.1 mm. This value is used to calculate the corresponding uncertainty component. The stated uncertainty value is given for a distance of 500 mm, a value often used in the measurements of 1 kW FEL-type lamps. The effect of repeatability was studied by repeating measurements with a test light source (also an FEL-type lamp). The diffraction effect is corrected and the remaining uncertainty component is estimated using the methods given in [27].

The relative uncertainty in the measurement of the aperture area given in [21] is stated.

The interreflection-induced uncertainty is estimated from the measured reflectance values in the passbands of the filters. Although the amount of back-reflected light from the trap detector is comparatively small, a fraction of light re-enters the detector by reflecting back from the filter and contributes to the photocurrent generated. The back-reflection from the surface facing the trap detector determines the correction to the measured signal. This correction increases from 1 part in 10^4 in the NIR to 7 parts in 10^3 in the UV. The correction was tested by measuring an FEL-type lamp with the filter radiometer in which a transmission trap detector was used. The six-element transmission trap detector [28] has no back-reflection. The spectral irradiance values derived from the results of measurements with the transmission trap detector were thus expected to be lower than those obtained from the reflection trap detector. However, within the uncertainty of the measurements, we did not see any significant differences in the values of spectral irradiance. We therefore conclude that the correction we are applying takes the effect of interreflection into account at a satisfactory level of accuracy.

The interpolation-induced uncertainty component is calculated as a standard deviation of the differences between the calculated and measured spectral irradiance values at the effective wavelengths λ_{eff}. Interpolation at the wavelength of 291 nm causes increased uncertainty because of the complex structure of the spectral emissivity, which cannot be entirely accounted for using a polynomial fitting.

4. Results

We have measured several 1 kW FEL-type lamps to test the applicability of our method. One of the lamps, F-491, is directly traceable to the NIST and serves as a primary standard of spectral irradiance at the Radiation and Nuclear Safety Authority, Helsinki (STUK). The distance between the alignment jig of the lamp and the plane of the high-precision aperture of the filter radiometer was set to 500 mm. The uncertainty of the distance setting at the STUK was somewhat larger than that at the HUT, i.e. 0.5 mm, owing to a different method of distance adjustment.

At the HUT, a similar set-up was used in measurements of the other lamps (S/NL00011, S/NL00014, S/NL00017) calibrated at the PTB. These lamps were operated using a detector-stabilized power supply [29]. The distance between the reference plane on the lamp housing and the high-precision aperture of the filter radiometer was 700 mm.

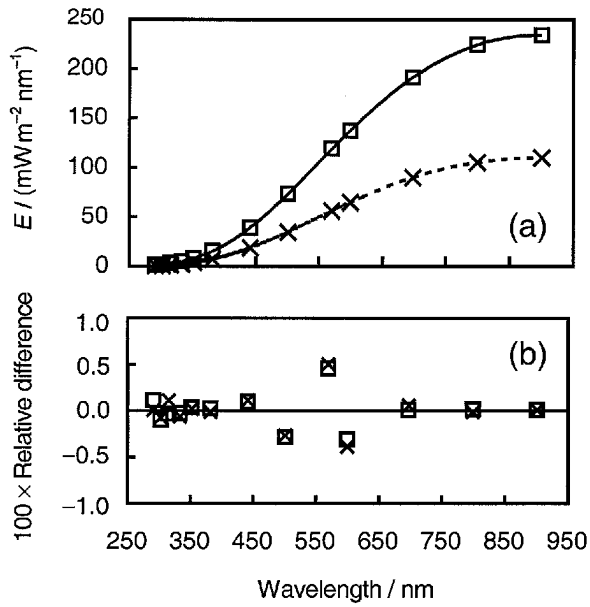

Figure 6. Spectral irradiance of two 1 kW FEL-type lamps: (a) measured values of the spectral irradiance at effective wavelengths of the filters (□ F-491; × S/NL00014) and the interpolated spectra (curves); (b) relative difference between measured and interpolated values.

Figure 6 shows the irradiance spectra of two lamps. The agreement between the measured and the interpolated values is better than 5 parts in 10^3 (Figure 6b). The standard deviation of the data is less than 3 parts in 10^3.

Figure 7 compares the spectral irradiance values derived for lamp F-491 with those given by the NIST [30]. The comparison indicates that the spectral irradiance values assigned to lamp F-491 at the HUT are higher than the NIST values. The maximum deviation of –3 parts in 10^2 occurs near the wavelength of 300 nm.

The results of the comparison of the spectral irradiance values between the HUT and the PTB show that the HUT irradiance values are lower than those of the PTB [31]. The maximum difference is +2.2 parts in 10^2, around the wavelength of 350 nm (Figure 7).

The deviation of relative differences in spectral irradiance values measured by the HUT from the average of differences shows a structure at UV wavelengths. Analysis has shown that this structure is partially due to the responsivity values of the trap detector.

5. Reproducibility of spectral irradiance measurements

The long-term reproducibility of the spectral irradiance measurements was investigated by measuring a NIST-traceable FEL-type lamp (F-434) three times: in May 1998, in March 1999, and in February 2000. Figure 8 presents the results of the measurements. The relative differences between the spectral irradiance values of

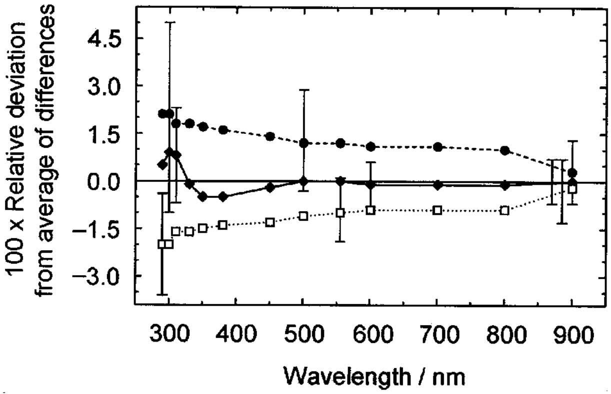

Figure 7. Relative deviations from the arithmetic average of the differences between the spectral irradiance values of the HUT (♦), the PTB (●) and the NIST (□) determined for the lamps S/NL00014 and F-491. The reference of zero deviation is located at a wavelength of 900 nm, where the deviations and the measurement uncertainties are the lowest. Bars indicate the expanded uncertainty.

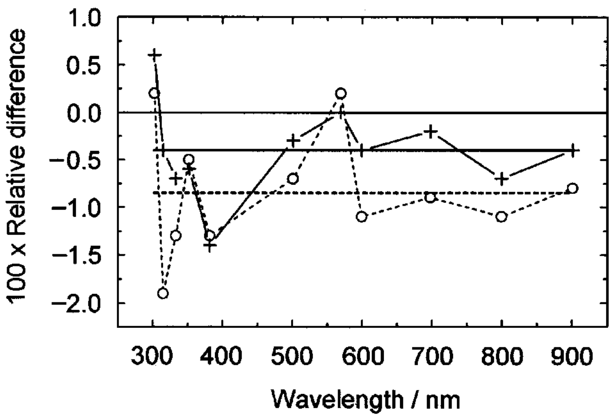

Figure 8. Relative differences between the spectral irradiance values determined by the HUT for the FEL-type lamp F-434 normalized to those obtained in May 1998: March 1999 (+, solid line) and February 2000 (○, dashed line). Bold lines represent the changes in the spectral irradiance values arising from ageing of the lamp: solid and dashed lines respectively indicate the drop of –0.4 % over one year and of –0.8 % over two years. When ageing is taken into account, the reproducibility of spectral irradiance measurements is better than ±1 % in the UV and ±0.3 % in the VIS-NIR.

three successive measurements show the effect of ageing on the radiation output of the lamp. On average, the spectral irradiance of the source was observed to decrease by 4 parts in 10^3 per year, in spite of minimal use (0.5 h) between each measurement. When the effect of ageing is taken into account, the reproducibility estimates are better than 1 part in 10^2 in the UV and 3 parts in 10^3 in the VIS-NIR wavelength ranges, well within the standard uncertainties of HUT measurements. During the period of observation, the filters were calibrated twice a year, the trap detector was calibrated once a year, and the high-precision aperture was recalibrated once after two years. The good reproducibility of the spectral irradiance values supports the choice of calibration intervals for the components of our filter radiometer.

6. Conclusions

We have extended the trap-detector-based method for absolute spectral irradiance measurements into a wide wavelength interval, from 290 nm to 900 nm. The uncertainty of the scale realization varies between 2.7 parts in 10^2 and 7 parts in 10^3 ($k = 2$), being larger at UV wavelengths and smaller in the VIS-NIR range.

The measurement method is based on a filter radiometer, whose components are separately characterized. Our filter radiometer is composed of a silicon-based trap detector, a set of temperature-controlled filters and a high-precision aperture. In the near-UV, a new interpolation method for the spectral responsivity of the trap detector has been implemented. Thirteen temperature-stabilized filters are used in the measurements of the absolute spectral irradiance. The need for stabilization has been tested by the temperature-sensitivity measurements. Changes in the integral transmittance of the order of ±4 parts in 10^3 have been observed for some of the filters, when the temperature is varied by ±7 °C from the normally used value of 25 °C.

The spectral irradiance values derived at the HUT have been compared with those of the NIST and the PTB. The HUT values are between those of the NIST and the PTB. The maximum differences are +3 parts in 10^2 and –2.2 parts in 10^2 compared with the spectral irradiance values of the NIST and the PTB, respectively, around the 300 nm to 350 nm wavelength interval. Somewhat larger deviations were obtained in the comparisons of spectral irradiance scales organized by the CCPR [8, 9]. In the VIS-NIR, the deviation of the HUT values from those of the NIST and the PTB is even lower: around 1 part in 10^2 on average.

The reproducibility of the spectral irradiance measurements has been tested by measuring an FEL lamp three times over two years. The results show that the reproducibility is better than ±1 part in 10^2 in the UV and ±3 parts in 10^3 in the VIS-NIR. The good agreement of the comparison results and the reproducibility of the measurements demonstrate the applicability of the method we have chosen for detector-based measurements of spectral irradiance in the wavelength range 290 nm to 900 nm.

Acknowledgements. The authors thank Pasi Toivanen for accurate measurements of the high-precision aperture used in these measurements and Klaus D. Stock (PTB) for arranging the comparison of the spectral irradiance scales. Financial support from the Centre for Metrology and Accreditation (Finland) and the Academy of Finland is gratefully acknowledged. Petri Kärhä thanks the Emil Aaltonen Foundation.

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Received on 14 April 2000 and in revised form on 29 May 2000.