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A spectrally tunable calibration source using Ebert-Fastie configuration

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Abstract

A novel spectrally tunable calibration source based on a digital micromirror device (DMD) and Ebert-Fastie optical configuration with two working modes (narrow-band mode and broad-band mode) was designed. The DMD is set on the image plane of the first spectral tuner, and controls the wavelength and intensity of the light reflected into the second spectral tuner by switching the micromirror array's condition, which in turn controls the working mode of the spectrally tunable source. When working in narrow-band mode, the spectrally tunable source can be calibrated by a Gershun tube radiant power radiometer and a spectroradiometer. In broad-band mode, it can be used to calibrate optical instruments as a standard spectral radiance source. When using a xenon lamp as a light source, the stability of the spectrally tunable source is better than 0.5%, the minimum spectral bandwidth is 7 nm, and the uncertainty of the spectral radiance of the spectrally tunable source is estimated as 14.68% at 450 nm, 1.54% at 550 nm, and 1.48% at 654.6 nm. The uncertainty of the spectral radiance of the spectrally tunable source calibrated by the Gershun tube radiometer and spectroradiometer can be kept low during the radiometric calibration procedure so that it can meet the application requirement of optical quantitative remote sensing calibration.

Keywords: radiometry, sources, optical instruments

(Some figures may appear in colour only in the online journal)

1. Introduction

On account of their ability to simulate flexible spectrum distribution accurately and efficiently, spectrally tunable sources have become a hotspot in artificial light source research, and are widely studied and used in biology, radiometry, photometry, colorimetry, and optical instrument calibration [1–4]. Therefore, spectrally tunable sources have been developed to meet various requirements. Traditionally, the method to form a spectrally tunable source is to combine filters and sources with different spectrum distributions (e.g. a light-emitting diode-based spectrally tunable source for star simulators [5]). However, there are always some disadvantages, such as low efficiency, high cost, relatively low spectral resolution, and low matching accuracy toward the target spectrum. In recent years, with the development of micro optoelectro mechanical system, spectrally tunable sources based on spatial light modulators (SLMs), like the digital micromirror device (DMD), have become a research focus. This is because of their advantages of high convenience and high matching accuracy toward a flexible target spectrum.

As a convenient SLM device with good flexibility and stability, the DMD has been used in many spectrally tunable source studies. In 2005, MacKinnon constructed a programmable spectral engine with a DMD and a high efficiency optical system using an anamorphic concentrator to create various spectral profiles for biochemistry and biomedicine applications [1]. Brown *et al* suggested spectrally tunable sources for radiometric applications [3], and then constructed a spectrally tunable source using the OneLight Spectral Engine for application in high accuracy radiometric calibration [4]. In 2016, Zhai *et al* reported the design of a DMD spectrally tunable source using a prism as a dispersing device [6], while Ma *et al* described a convex grating Offner configuration spectrally tunable source [7].

The different designs mentioned above are mainly based on a single grating/prism monochromator configuration. In this paper, a new kind of spectrally tunable calibration source based on a double-subtractive Ebert-Fastie spectrometer configuration is proposed to meet the requirement of high accuracy radiometric calibration. In the sections below, the principle and configuration of the spectrally tunable source are illustrated in detail, and several experiments are carried out to verify the design and test the performance of the system.

2. Configuration and operating principles

2.1. Optical configuration and operating process

As shown in figure 1, the spectrally tunable calibration source consists of a light source with condensers (here we used a conventional high stability xenon lamp), a spectral tuner, a liquid light guide, an integrating sphere, a spectroradiometer, and a Gershun tube radiometer. The spectroradiometer is used to monitor the output radiance of the spectrally tunable source. It is calibrated by a standard radiance source.

The configuration of the double-subtractive Ebert-Fastie spectral tuner consists of an entrance slit, an exit slit, two plane gratings, two concave mirrors, and a DMD; this configuration is similar to that of an Ebert-Fastie grating spectrometer. The DMD is set on the focal plane of the first concave mirror. The schematic diagram of the optical path and the spectrally tunable source configuration is shown in figure 1. The working wavelength band is 400 nm–700 nm, the grating groove density is 150 g mm^{-1}, and the curvature radius of the two concave mirrors is 500 mm. The diameter of the integrating sphere is 135 mm. The internal surface of the integrating sphere is covered by polytetrafluoroethylene.

DMD is a commercially available device from Texas Instruments. We adopted a DLP7000 DMD chip in this research. The DMD is a 2D tiltable aluminum micromirror array, including 1024×768 micromirrors (each mirror is $13.68\,\mu$m $\times$ $13.68\,\mu$m in size). Each mirror can be addressed individually, and set to either $+12°$ (named 'on') or $-12°$ (named 'off') electronically, thereby directing the light either toward or away from the target direction. The DMD can be controlled by a computer with good flexibility and stability, thereby ensuring the convenience and accuracy of the spectrally tunable source.

The operating principle of the spectrally tunable source is as follows: light emitted from the xenon lamp is focused by the condensers at the entrance slit of the first spectral tuner. In the spectral tuner, light from the entrance silt is collimated by the first concave mirror, and then dispersed by the first grating. Then the first dispersion is imaged by the first concave mirror on the surface of the DMD. The light reflected from the DMD is collimated again by the second concave mirror, synthesized to quasi-monochromatic light by the second grating, and focused at the exit slit by the second concave mirror. The light out of the exit slit is finally guided into the integrating sphere through the liquid light guide, forming a uniform spectral radiance source. The 1024 columns of micromirrors correspond to wavelengths, while the 768 rows correspond to the intensity of light of a specific wavelength. By controlling which micromirrors to be set 'on', lights of specific wavelengths and intensities can be picked out and then synthesized together, forming a new source with a different spectrum.

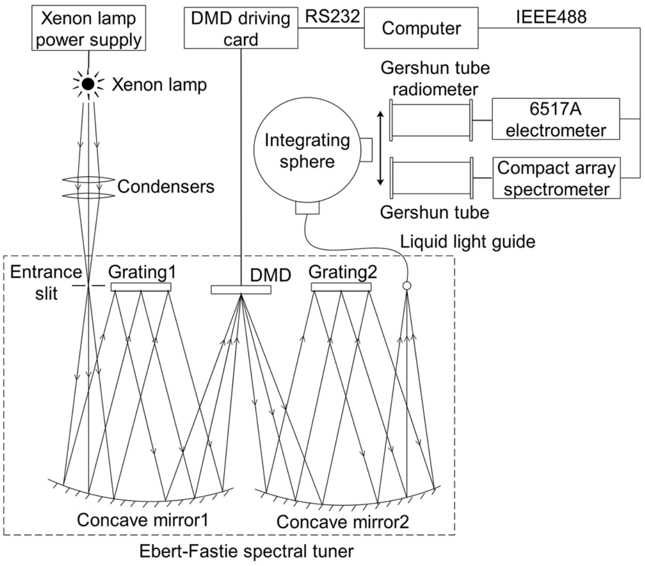

Figure 1. Configuration diagram of the spectrally tunable source.

2.2. Calibration principle of the spectrally tunable source

There are two working modes of the spectrally tunable source: the broad-band mode and narrow-band mode. We equally divide the 1024 columns of micromirrors into N groups, which means N spectral channels. In broad-band mode, when all the groups are set to 'on', the DMD reflects all incident light into the optical path. At this time, the output of the integrating sphere is 'white light' of a broad wavelength band. In narrow-band mode, only one of the groups is set 'on', and the light of corresponding wavelengths is reflected into the optical path. At this time, the output of the integrating sphere is quasi-monochromatic light of a narrow wavelength band. In narrow-band mode, all the spectral channels are calibrated by the Gershun tube radiometer so that the spectral radiance distribution of the integrating sphere output corresponding to each spectral channel can be achieved accurately. In broad-band mode, we can get the spectral radiance distribution of the 'white light' by accumulating the spectral radiance distributions of all the spectral channels so that the accuracy of the spectrally tunable source can be ensured.

We used a spectroradiometer calibrated by a standard spectral radiant source based on a calibrated FEL lamp to measure the spectrally tunable source. The spectroradiometer consists of a CAS 140CT-152 compact array spectrometer and fiber-based input optics with a Gershun tube. The CAS 140CT-152 spectrometer is a commercially available spectrometer whose working spectral range is 200 nm–800 nm, and spectral resolution is 2.7 nm. By changing the density filters integrated inside and adjusting the integration time of the CCD,

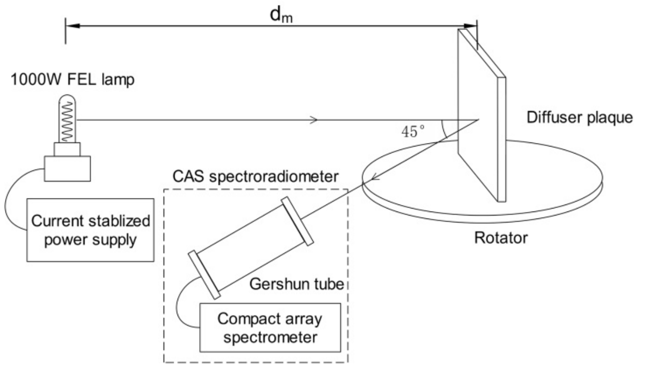

Figure 2. Spectroradiometer calibration setup diagram.

the spectrometer can achieve a dynamic range of 10^9. The light is guided into the spectrometer through an optical fiber. The other end of the optical fiber is naked and exposed, and therefore a Gershun tube is needed to restrict the field-of-view (FOV) of the spectrometer. The Gershun tube is mounted in front of the end of the optical fiber, with a designed 5.6° FOV.

We used a 1000 W FEL lamp calibrated by the National Institute of Standard and Technology (NIST), and a Labsphere Spectralon diffuser plaque with $8°/\text{hemisphere}$ reflectance data (calibrated by Labsphere) as a standard spectral radiance source, to calibrate the spectrally tunable source. The schematic diagram of the calibration setup is shown in figure 2. The spectral radiance responsivity $R_{\text{CAS}}(\lambda)$ of the spectroradiometer can be expressed as follows [8]:

$$R_{\text{CAS}}(\lambda)=\frac{S_{\text{b}}(\lambda)}{L_{\text{b}}(\lambda)}=\frac{S_{\text{b}}(\lambda)}{\frac{F(8°/\text{hem},\lambda)}{\pi}\frac{d_{\text{ref}}^2}{d_{\text{m}}^2}E_{\text{b}}(\lambda)}=\frac{d_{\text{m}}^2}{d_{\text{ref}}^2}\frac{\pi S_{\text{b}}(\lambda)}{F(8°/\text{hem},\lambda)\,E_{\text{b}}(\lambda)},\tag{1}$$

where λ is the wavelength of the light, $S_{\text{b}}(\lambda)$ is the signal of the spectroradiometer when measuring the radiance of the plaque, $L_{\text{b}}(\lambda)$ is the spectral radiance of the Spectralon plaque illuminated by the 1000 W FEL lamp to the direction of the spectroradiometer, $F(8°/\text{hem},\ \lambda)$ is the $8°/\text{hemisphere}$ reflectance of the Spectralon plaque, $E_{\text{b}}(\lambda)$ is the calibrated spectral irradiance of the FEL lamp at the reference distance d_{ref}, $d_{\text{ref}}=500\,\text{mm}$, and d_{m} is the measured distance between the FEL lamp and the diffuser plaque, as shown in figure 2.

In equation (1), 0/45 reflectance should be used when calibrating the spectroradiometer. However, since we do not have the uncertainty of 0/45 reflectance, the $8°/\text{hemisphere}$ reflectance is instead adopted in order to estimate the uncertainty of the relative spectral radiance of the spectroradiometer. The uncertainty caused by the deviation of the $8°/\text{hemisphere}$ reflectance and 0/45 reflectance should be added to the uncertainty estimation in section 3 (shown in table 3).

The radiance responsivity $R_{\text{CAS}}(\lambda)$ of the spectroradiometer can be derived from equation (1). The result is shown in figure 3.

As we divide the 1024 columns of micromirrors of the DMD into N groups, the absolute spectral radiance of the spectrally tunable source can be derived from

$$L_{mx}(\lambda)=\frac{S_{mx}(\lambda)}{R_{\text{CAS}}(\lambda)},\tag{2}$$

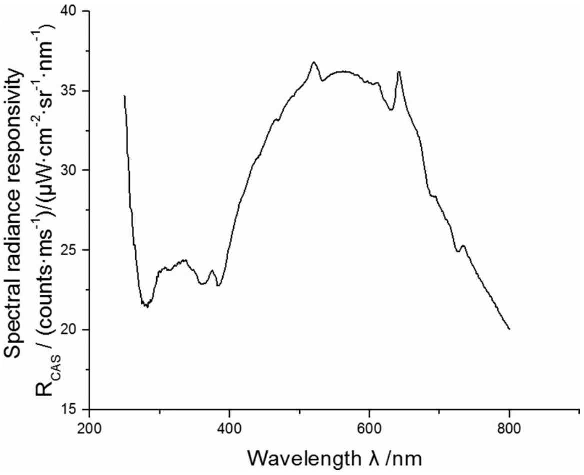

Figure 3. Spectral radiance responsivity for the spectroradiometer.

$$L_{0x}(\lambda)=\frac{S_{0x}(\lambda)}{R_{\text{CAS}}(\lambda)},\tag{3}$$

where $L_{mx}(\lambda)$ and $L_{0x}(\lambda)$, respectively, are the measured spectral radiance of the integrating sphere of the spectrally tunable source in narrow-band mode and broad-band mode, $S_{mx}(\lambda)$ and $S_{0x}(\lambda)$, respectively, are the reading signals of the spectroradiometer in narrow-band mode and broad-band mode, and m is the ordinal number of the micromirror groups ($m=1$ to N).

By accumulating the narrow-band mode spectral radiance $L_{mx}(\lambda)$, the spectral radiance distribution in broad-band mode can be derived:

$$L'_{0x}(\lambda)=\sum_{1}^{N}L_{mx}(\lambda)=\sum_{1}^{N}\frac{S_{mx}(\lambda)}{R_{\text{CAS}}(\lambda)},\tag{4}$$

where $L'_{0x}(\lambda)$ is the accumulated spectral radiance of $L_{mx}(\lambda)$.

To measure the spectral radiance of the spectrally tunable source more accurately, a Gershun tube radiometer using a silicon photodiode calibrated by NIST and traceable to absolute cryogenic radiometer is designed [9]. The Gershun tube radiometer is made up of a Gershun tube and a Hamamatsu silicon photodiode S2281 with a calibrated spectral range of 200 nm to 1100 nm. Its structure is shown in figure 4. The Gershun tube is designed to restrict the FOV of the silicon photodiode to 5.6°. The front aperture diameter D is $11.607\,\text{mm}\pm3.2\,\mu\text{m}$, the detector aperture diameter d is $5.061\,\text{mm}\pm3.1\,\mu\text{m}$, and the distance h between them is $169.575\,\text{mm}\pm2.4\,\mu\text{m}$. The spectral radiant power responsivity of the silicon photodiode calibrated by NIST is shown in figure 5; its calibration uncertainty is 0.75%–0.2% from 400 nm to 700 nm ($k=2$). The output of the Gershun tube radiometer is measured by the Keithley 6517A electrometer, and then the signal is transferred to the computer through the IEEE488 interface for data acquisition and processing. According to the measured value from the Gershun tube radiometer, the output of the spectrally tunable source in narrow-band mode is adjusted to compensate for the ageing and the decay effect of the spectrally tunable radiant source through the DMD during calibration for

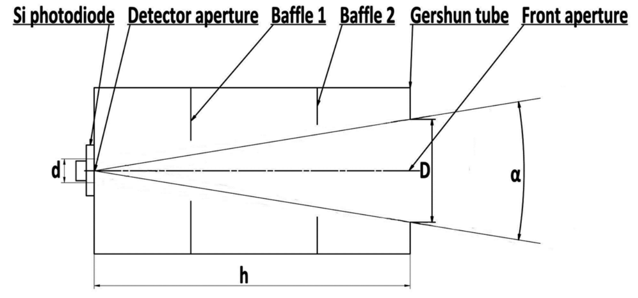

Figure 4. Structure diagram of the Gershun tube radiometer.

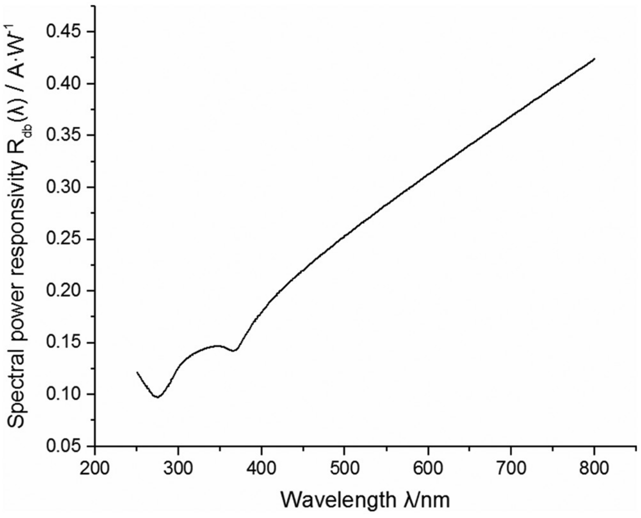

Figure 5. Spectral power responsivity of the silicon photodiode.

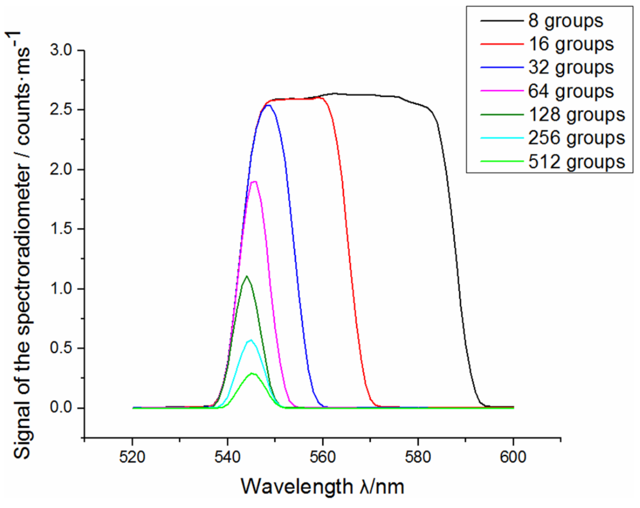

Figure 6. Spectral bandwidths of the spectrally tunable source of 8, 16, 32, 64, 128, 256, and 512 DMD subdivisions in narrow-band mode.

remote sensing instruments. Therefore, the spectral radiance of the spectrally tunable source system in broad-band mode is kept stable.

In narrow-band mode, all the N spectral channels of the spectrally tunable source are measured with the Gershun

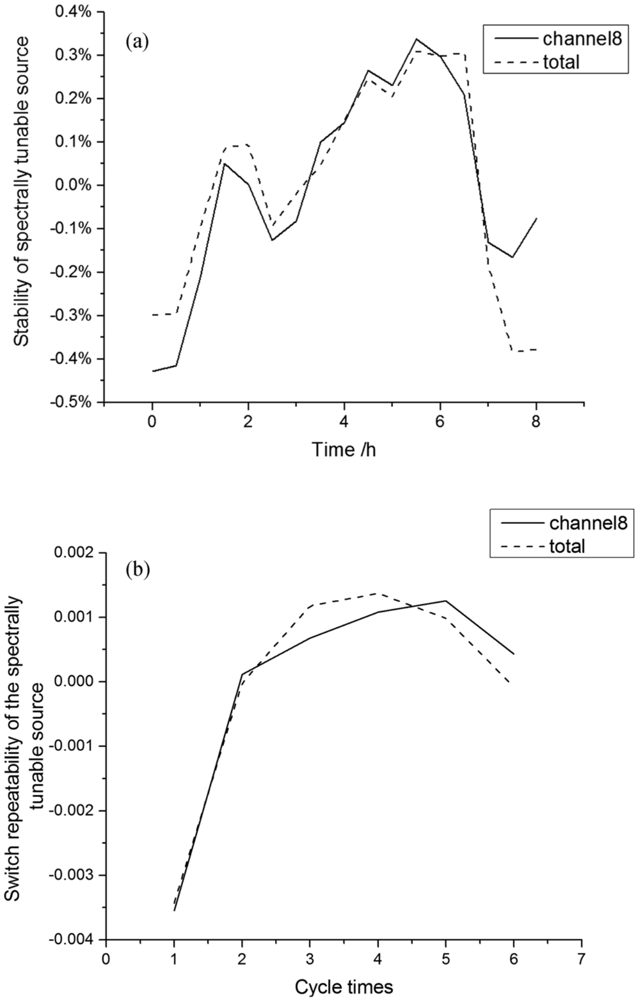

Figure 7. (a) Stability of the spectrally tunable source in narrow-band mode (channel 8) and broad-band mode during 8 h. (b) Switch repeatability of the spectrally tunable source in narrow-band mode (channel 8) and broad-band mode during six cycles.

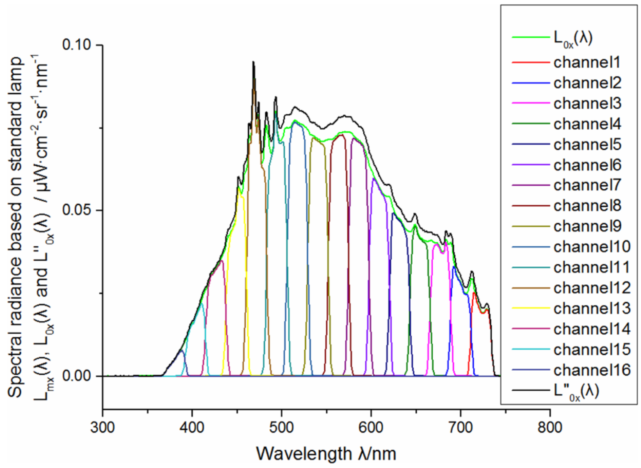

Figure 8. Spectral radiance curves in two working modes: channel 1 to channel 16 for signals measured in narrow-band mode, $L_{0x}(\lambda)$ for the signal measured in broad-band mode, and L''_{0x} for the broad-band mode signal corrected by the Gershun tube radiometer.

Table 1. A typical group of measured signal S_{dm}, integrated signal S'_{dm}, and their ratio η_m.

Spectral channel	Integrated signal S'_{dm} (nA)	Measured signal S_{dm} (nA)	Ratio η_m
1	0.143 106	0.151 179	1.0564
2	0.183 066	0.193 120	1.0549
3	0.239 390	0.249 858	1.0437
4	0.243 915	0.257 710	1.0566
5	0.263 180	0.275 714	1.0476
6	0.308 482	0.320 490	1.0389
7	0.363 582	0.378 797	1.0418
8	0.354 435	0.370 494	1.0453
9	0.336 428	0.347 433	1.0327
10	0.340 335	0.350 303	1.0293
11	0.303 413	0.315 059	1.0384
12	0.288 566	0.299 766	1.0388
13	0.184 013	0.191 215	1.0391
14	0.108 356	0.111 999	1.0336
15	0.053 891	0.056 529	1.0490
16	0.013 518	0.015 394	1.1388

tube radiometer. The output of each spectral channel can be expressed as follows [9]:

$$\Delta S'_{dm}(\lambda) = R_{\mathrm{d}}(\lambda) \cdot L_{mx}(\lambda) \cdot \omega_{\mathrm{d}} \cdot A_{\mathrm{d}} \tag{5}$$

where $R_{\mathrm{d}}(\lambda)$ is the absolute spectral radiant power responsivity of the silicon photodiode, $L_{mx}(\lambda)$ is the measured spectral radiance of the mth spectral channel of the spectrally tunable source in narrow-band mode, ω_{d} is the viewing solid angle of the Gershun tube radiometer, $\omega_{\mathrm{d}} = 2\pi(1 - \cos\alpha/2)$, A_{d} is the effective area of the detector aperture, and $A_{\mathrm{d}} = \pi d^2/4$.

By integrating equation (5), the overall output of the mth spectral channel of the Gershun tube radiometer can be derived as follows:

$$S'_{dm} = \int R_{\mathrm{d}}(\lambda) L_{mx}(\lambda) \omega_{\mathrm{d}} A_{\mathrm{d}} \mathrm{d}\lambda = \omega_{\mathrm{d}} A_{\mathrm{d}} \int R_{\mathrm{d}}(\lambda) L_{mx}(\lambda) \mathrm{d}\lambda, \tag{6}$$

where S'_{dm} is the integration value of $\Delta S'_{dm}(\lambda)$.

To calculate S'_{dm}, we discretized equation (6) as

$$S'_{dm} = \omega_{\mathrm{d}} A_{\mathrm{d}} \sum R_{\mathrm{d}}(\lambda) L_{mx}(\lambda), \tag{7}$$

where the range of summation is 250 nm to 800 nm, and the increment is 0.1 nm.

Because of the uncertainty of the measured value of the Gershun tube radiometer and the uncertainty of the calculated value $\omega_{\mathrm{d}} A_{\mathrm{d}} \int R_{\mathrm{d}}(\lambda) L_{mx}(\lambda) \mathrm{d}\lambda$, the calculated value is not equal to the measured value. To modify the deviation caused by uncertainties, a coefficient η_m is employed:

$$S_{dm} = \eta_m \cdot S'_{dm}, \tag{8}$$

where S_{dm} is the measured value of the Gershun tube radiometer.

The Gershun tube radiometer is a radiometer that measures the spectral radiant power, and thus we cannot obtain the absolute spectral radiance through equation (6) or (7) without knowing the spectrum distribution shape of the spectrally tunable source in narrow-band mode. To calibrate each spectral channel with the Gershun tube radiometer, we can first measure the spectral radiance with the spectroradiometer and Gershun tube radiometer. Then, the calculated signal S'_{dm}, the measured signal S_{dm}, and the modifying coefficient η_m, can be acquired through equations (7) and (8). Finally, we can use the modifying coefficient η_m to correct the spectral radiance of the spectrally tunable source measured by the spectroradiometer. Therefore, the absolute spectral radiance L''_{0x} in broad-band mode calibrated by the Gershun tube radiometer can be expressed as

$$L''_{0x} = \sum_{1}^{N} \eta_m \cdot L_{mx}(\lambda). \tag{9}$$

In this way, we can calibrate the spectrally tunable source in narrow-band mode based on the Gershun tube radiometer, and in turn acquire the absolute spectral radiance in broad-band mode with a better uncertainty.

3. Performance of the spectrally tunable source

3.1. Spectral bandwidth of the spectrally tunable source

In narrow-band mode, the spectral resolution of the spectrally tunable source is related to how many columns of micromirrors are set 'on'. The spectral bandwidths of the 4th, 8th, 16th, 32th, 64th, 128th, and 256th spectral channel when we divided the DMD into 8, 16, 32, 64, 128, 256, and 512 groups, respectively, are shown in figure 6. We can see that the spectral bandwidth can achieve 7 nm when the subdivision is 64, and when the subdivision of the DMD increases to 128, 256, and 512, the spectral bandwidths are still about 7 nm; meanwhile, the spectral power decreases greatly.

3.2. Stability of the spectrally tunable source

The stability of the spectrally tunable source is measured by the Gershun tube radiometer in narrow-band mode (e.g. channel 8) and broad-band mode after 20 min preheating. The short-term stability is smaller than ±0.3% within 1 h, and the long-term stability is smaller than ±0.5% within 8 h, as shown in figure 7(a). The switch repeatability was measured by the Gershun tube radiometer in broad-band mode and narrow-band mode (e.g. channel 8) after 20 min preheating and 10 min power off (named one cycle). The switch repeatability of the spectrally tunable source is smaller than ±0.4%, as shown in figure 7(b).

3.3. Measurement results of spectral radiance

As described in section 2, the absolute spectral radiance of the spectrally tunable source in narrow-band mode and broad-band mode is measured by the spectroradiometer, which is calibrated based on a standard lamp. The absolute spectral radiance of channel 1 to channel 16 ($L_{mx}(\lambda)$, $m = 1$ to 16), and the absolute spectral radiance measured in broad-band mode ($L_{0x}(\lambda)$), are shown in figure 8.

Table 2. Uncertainty of the Gershun tube radiometer-based spectral radiant power measurement in narrow-band mode.

Uncertainty sources	Uncertainty magnitude		
	450 nm	555 nm	654.6 nm
Uncertainty of the spectral radiant power responsivity of the silicon photodiode	0.12%	0.11%	0.10%
Reading uncertainty of the electrometer	0.02%	0.02%	0.02%
Spatial response homogeneity of the silicon photodiode	0.1%	0.1%	0.1%
Angular response homogeneity of the silicon photodiode	0.16%	0.16%	0.16%
Geometric size accuracy for the diameters and distance of the apertures in the Gershun tube radiometer	0.09%	0.09%	0.09%
Combined uncertainty	0.24%	0.24%	0.23%
Expanded uncertainty ($k = 2$)	0.48%	0.48%	0.46%

Table 3. Uncertainty of relative spectral radiance measurement of the source (shape of spectrum distribution).

Uncertainty sources	Uncertainty magnitude		
	450 nm	555 nm	654.6 nm
Relative spectral irradiance uncertainty for standard FEL lamp	0.45%	0.39%	0.35%
Effects of the spectroradiometer bandpass function	7.16%	0.40%	0.36%
Wavelength accuracy of the spectroradiometer	1.44%	0.03%	0.16%
Reading repeatability of the spectroradiometer	0.2%	0.2%	0.2%
Uncertainty of 8°/hemisphere reflectance of the Spectralon plaque	0.27%	0.27%	0.25%
Deviation between 8°/hemisphere and 0/45 reflectance	0.09%	0.09%	0.09%
Stability of the FEL lamp power supply	0.03%	0.03%	0.03%
Linearity of the spectroradiometer	0.17%	0.17%	0.17%
Combined uncertainty	7.33%	0.68%	0.65%
Expanded uncertainty ($k = 2$)	14.66%	1.36%	1.30%

Table 1 shows a typical series of the measured signal S_{dm}, the integrated signal S'_{dm} of the Gershun tube radiometer, and their ratio η_m. As described in section 2, η_m is used to correct the spectral radiance $L_{0x}(\lambda)$ measured in broadband mode. The corrected spectral radiance $L''_{0x}(\lambda)$ is shown in figure 8 (curve L''_{0x}). As discussed in section 2, the deviation between the integrated signal S'_{dm} and the measured signal S_{dm} shown in table 1 (2.93%–13.88%) is caused by the uncertainties of the Gershun tube radiometer measurement and the spectroradiometer measurement. The spectral range of the spectrally tunable source is designed to be 400 nm–700 nm, and in figure 8 we can see that channel 1 and channel 16 are partly or totally outside this range. The signal of the spectral radiance out of 400 nm–700 nm is quite small (its signal-to-noise ratio is about 10), and thus the deviation between the S'_{dm} and S_{dm} of channel 1 and channel 16 is reasonably larger.

3.4. Uncertainty analysis

Since the spectral radiance of the spectrally tunable source is first measured by the spectroradiometer and then corrected by the Gershun tube radiometer, the uncertainty of the spectral radiance is finally determined by the uncertainty of the spectroradiometer-based relative spectral radiance distribution measurement and the Gershun tube radiometer-based spectral radiant power measurement in narrow-band mode.

Table 2 shows the uncertainty estimation of the Gershun tube radiometer-based spectral radiant power measurement. The uncertainty of the spectral radiant power responsivity and the spatial homogeneity of the NIST silicon photodiode is from the calibration report issued by NIST. Since the FOV of the Gershun tube radiometer is 5.6°, the maximum incident angle of the light illuminated on the photodiode can be estimated as ±2.8°; then, we can get the deviation caused by the angular response of the photodiode from [10].

Table 3 shows the uncertainty estimation of the spectroradiometer-based relative spectral irradiance distribution measurement. Uncertainty of the relative spectral irradiance of the standard FEL lamp is in fact the same as that of the absolute spectral irradiance of the lamp (from the calibration report of the FEL lamp). This is because the deviation of the relative spectral irradiance distribution should be within the range of the absolute spectral irradiance deviation. The deviation between the measured relative spectral radiance and the 'true' spectral radiance caused by the instrument bandpass function of the spectroradiometer is estimated experimentally by comparing the spectral radiance of the xenon lamp measured under 2.7 nm spectral resolution (the same as the spectral resolution of the spectroradiometer) and 0.03 nm spectral resolution (the approximated 'true' spectrum), respectively. The wavelength accuracy of the spectroradiometer is 0.3 nm (from the CAS spectrometer user manual). The uncertainty magnitude of the bandpass function effect and the wavelength accuracy at 450 nm is quite large because the uncertainty caused by the bandpass function and the wavelength accuracy is sensitive to the steep slopes or spectral lines of the xenon lamp spectrum in the range of 450 nm to 500 nm (Figure 8). Therefore, the spectrally tunable source may not be used for high-accuracy calibration in the spectral range of 450 nm to 500 nm when a xenon lamp is used as the light source. The uncertainty of 8°/hemisphere reflectance of the Spectralon plaque is from its calibration report issued by Labsphere. The deviation between the 8°/hemisphere and 0/45 reflectance is as illustrated in section 2.2. The linearity of the spectroradiometer is in fact the linearity of the CAS spectrometer, whose uncertainty is provided by its user manual.

Table 4 shows the combined standard uncertainty of the spectral radiance of the spectrally tunable calibration source.

Table 4. Uncertainty of the spectral radiance of the spectrally tunable calibration source.

Uncertainty sources	Uncertainty magnitude 450 nm	 555 nm	 654.6 nm
Uncertainty of the Gershun tube radiometer-based measurement	0.24%	0.24%	0.23%
Uncertainty of relative spectral radiance measurement of the source	7.33%	0.68%	0.65%
Responsivity accuracy of the silicon photodiode caused by the wavelength deviation of the spectroradiometer	0.1%	0.1%	0.1%
Algorithm uncertainty of the narrow-band to broad-band switch	0.25%	0.25%	0.25%
Combined uncertainty	7.34%	0.77%	0.74%
Expanded uncertainty ($k = 2$)	14.68%	1.54%	1.48%

The wavelength deviation of the spectroradiometer may cause deviation to the responsivity value of the photodiode while calculating S'_{dm} (equation (8)). The 'algorithm uncertainty of the narrow-band to broad-band switch' is theoretically 0, but in fact it is experimentally determined to be 0.25%. This is due to many factors, such as stray light, the measurement accuracy of a weak dark signal, and so on.

4. Conclusion

A spectrally tunable calibration radiant source based on a Ebert-Fastie configuration and DMD has been developed. In narrow-band mode, the minimum spectral bandwidth is 7 nm. The stability is better than 0.5% during 8 h. The uncertainty of the spectral radiance of the spectrally tunable radiant source is estimated to be 14.68% at 450 nm, 1.54% at 550 nm, and 1.48% at 654.6 nm. It can be used for high-accuracy calibration for optical remote sensing instruments.

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