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Absolute detector-based spectrally tunable radiant source using digital micromirror device and supercontinuum fiber laser

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High-accuracy absolute detector-based spectroradiometric calibration techniques traceable to cryogenic absolute radiometers have made progress rapidly in recent decades under the impetus of atmospheric quantitative spectral remote sensing. A high brightness spectrally tunable radiant source using a supercontinuum fiber laser and a digital micromirror device (DMD) has been developed to meet demands of spectroradiometric calibrations for ground-based, aeronautics-based, and aerospace-based remote sensing instruments and spectral simulations of natural scenes such as the sun and atmosphere. Using a supercontinuum fiber laser as a radiant source, the spectral radiance of the spectrally tunable radiant source is 20 times higher than the spectrally tunable radiant source using conventional radiant sources such as tungsten halogen lamps, xenon lamps, or LED lamps, and the stability is better than ±0.3%/h. Using a DMD, the spectrally tunable radiant source possesses two working modes. In narrow-band modes, it is calibrated by an absolute detector, and in broad-band modes, it can calibrate for remote sensing instrument. The uncertainty of the spectral radiance of the spectrally tunable radiant source is estimated at less than 1.87% at 350 nm to 0.85% at 750 nm, and compared to only standard lamp-based calibration, a greater improvement is gained.

OCIS codes: (120.5630) Radiometry; (230.6080) Sources; (120.4640) Optical instruments.

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1. INTRODUCTION

In 2005, MacKinnon [1] presented a technical concept of a spectral tuner using a digital micromirror device (DMD) to meet color illuminating requirements in the research fields of biomedicine, biochemistry and spectroscopy, and constructed programmable spectral engine with a high efficiency optical system of anamorphic concentrator and applied for reproducing or creating various spectral profiles. In 2006, Brown *et al.* [2] suggested spectrally tunable DMD sources for advanced radiometric applications. Thereafter, Brown *et al.* [3] used a DMD OneLight spectral engine for development of absolute detector-based spectral radiance source applied for high-accuracy radiometric calibrations. At present, tungsten halogen lamps, xenon lamps, and light-emitting diodes (LEDs) are commonly used as radiant sources in spectral engines, but their spectral radiances generally are lower. To meet the requirements of radiometric calibrations of ground-based, aeronautics-based, and aerospace-based remote sensing instruments, and spectral simulations of solar, atmospheric, and other natural scenes, a high brightness spectrally tunable radiant source that uses a DMD and a supercontinuum fiber laser has been developed in this Changchun Institute of Optics, Fine Mechanics and Physics, and described in this paper. The spectral range of the spectrally tunable radiant source is from 400 nm to 700 nm, the stability is better than ±0.3%/h, and the spectral radiance is 20 times higher than the 300 W xenon lamp used as a radiant source. Based on the absolute detector calibration, the uncertainty of the spectral radiance is less than 1.87% at 350 nm to 0.85% at 750 nm. Compared to only standard lamp-based calibration, a greater improvement is gained.

2. STRUCTURE AND PRINCIPLE OF THE SPECTRALLY TUNABLE RADIANT SOURCE

The optical schematic diagram of the high-brightness spectrally tunable radiant source is shown in Fig. 1. It consists of a supercontinuum fiber laser, a beam expander, preoptics, a flat field spectrograph, a collecting lens, an integrating sphere, a Gershun tube radiometer, and a compact array spectrometer (CAS) spectroradiometer for monitoring and calibration. An EXB-6 high-power supercontinuum fiber laser of NKT Photonics is used. Its spectral region is from 400 nm to 2400 nm, the typical total radiation power is 3000 mW,

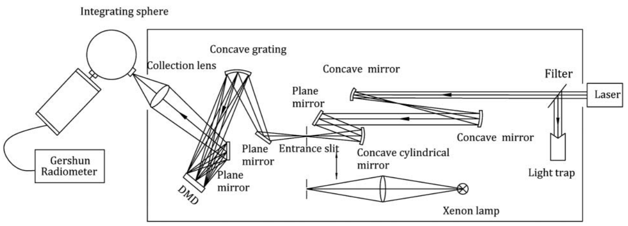

Fig. 1. High-brightness spectrally tunable radiant source optical and mechanical layout (top view). The optical and mechanical parts inside the rectangular frame is closed in an aluminum instrument case with a baseplate area of 810 mm × 305 mm and a case height of 320 mm.

and the visible radiation power is 600 mW. The laser beam from the fiber laser is guided into the spectrally tunable radiant source system through fiber. First, the infrared radiation part of the laser beam with a wavelength longer than 700 nm is reflected off by a cold filter. Then the beam is expanded to 25 mm in diameter after being reflected by two concave mirrors such that their curvature radii are 12 mm and 250 mm, respectively. The expanded laser beam was folded by a plane reflecting mirror and focused on the entrance slit of a $f/2.9$ flat-field spectrograph by a cylindrical reflecting mirror with a 100 mm curvature radius. The length of the narrow laser beam imaging is about 20 mm. The spectrograph uses a concave holographic reflectance grating with incident arm length 86.4 mm and exit arm length that depends on the wavelength of about 85 mm. The spectral range of the flat-field spectrograph is from 300 nm to 850 nm, the groove density of the concave grating is 430 grooves per mm, the reciprocal linear dispersion is 24.6 nm per mm, and the size of the spectrograph spectrum surface is 14 mm × 10.5 mm.

A DMD (TI DLP 7000) with a two-dimensional aluminum micromirror array of 1024 columns by 768 rows was placed on the spectrum plane of the concave grating of the flat-field spectrograph. Each aluminum micromirror is about 13.68 μm × 13.68 μm and rotatable around its diagonal line. The rotation is determined by the binary state of the SRAM under each micromirror through the electrostatic attraction effect. Each micromirror that can be programmatically controlled to tilt on a hinge is positioned diagonally relative to the array plane with ±12° angular positions corresponding to the DMD's either "on" or "off" state. The laser beam with the selected wavelength was reflected and then converged to an integrating sphere with interior diameter 135 mm through a collecting lens when one or a few columns of micromirrors are set to be "on" and formed a quasi-Lambertian uniform source. The part being set to be "off" was reflected to a beam dump. The number of micromirrors in one or a few columns that contributed to reflection is programmatically controlled. The light intensity reflected from micromirrors at the corresponding wavelengths can be adjusted to change the spectral distribution of the spectrally tunable source accordingly. This feature enables this type of radiant source to simulate the spectral distributions of natural scenes including sun, atmosphere, and objects on the ground. [4].

The spectrally tunable radiant source has two working modes from using a DMD. In broadband modes, incident light with a broad spectral band enters into the integrating sphere while all micromirrors of the DMD are turned "on" and the output of the integrating sphere source is "white light". In narrow-band modes, the incident light with a narrow spectral band enters into the integrating sphere while one or a few columns of DMD micromirrors are turned "on", and the output of integrating sphere source is quasi-monochromatic light. The quasi-monochromatic radiant flux from the integrating sphere source in narrow-band modes is monitored and calibrated with a CAS spectroradiometer and a Gershun tube radiometer. The spectral radiance of the integrating sphere source in broadband modes is obtained from the accumulation of these spectral radiances of all quasi-monochromatic spectral channels and will be used for spectroradiometric calibration for remote sensing instruments. The long-term stability of the absolute spectral radiance of the spectrally tunable radiant source is ensured by monitoring, correction, and self-calibration regularly in narrow-band modes by Gershun radiometers during the long-term radiometric calibration procedure in broadband modes.

3. RADIANT CHARACTERISTICS OF THE SPECTRALLY TUNABLE RADIANT SOURCE

A. Measurement and the Calibration Based on Spectral Radiance Standard

The spectral radiances of the spectrally tunable radiant source were measured by a Model CAS 140CT-152 spectrometer with spectral range 200 nm to 800 nm. The CAS spectrometer adopts optimized crossed Czerny–Turner spectrograph configuration with a ruled plane grating of blaze wavelength of 300 nm and a back-thinned two-dimensional CCD detector, which is stabilized to −10°C by a TEC device. The stray light level is 5×10^{-4} for a broadband illuminant. The dynamic range can reach to nine orders of magnitude by adjusting the integrated filter wheel equipped with four density filters and the change of CCD integration time. The light is guided to the entrance slit of the CAS spectrometer by an optical fiber. To restrict the field of view (FOV) of the CAS spectrometer, a Gershun tube with 5.6 deg FOV is mounted in front of the optical fiber head. The CAS spectrometer mounted with Gershun tube is called as CAS spectroradiometer to represent it is a CAS-based spectroradiometer.

To measure the absolute spectral radiances of the integrating sphere source, the spectral radiance responsivity of the CAS spectroradiometer was derived from a NIST calibrated and issued spectral irradiance standard 1000 W tungsten quartz-halogen lamp and Labsphere Spectralon plaques (diffusing reflectance panel) with known hemispherical reflectance. The optical schematic of the calibration device is shown in Fig. 2.

The averaged spectral radiance of the Spectralon plaques illuminated by the spectral irradiance standard lamp to the direction of the CAS spectroradiometer can be written [5] as

$$L_b(\lambda) = E_b(\lambda) \cdot \cos\theta \cdot \mathrm{BRDF} \cdot W(x, y) f(x, y), \quad (1)$$

where $E_b(\lambda)$ is the spectral irradiance of the NIST 1000 W tungsten quartz-halogen standard lamp;θ is the angle between the normal of the plaques and the optical axis of the Gershun tube of the CAS spectroradiometer; $W(x, y)$ is the correction

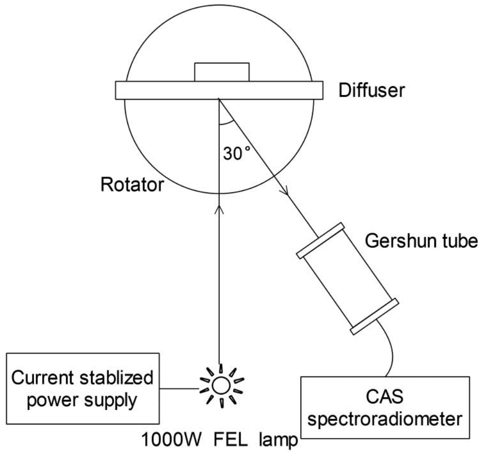

Fig. 2. CAS spectroradiometer calibration device.

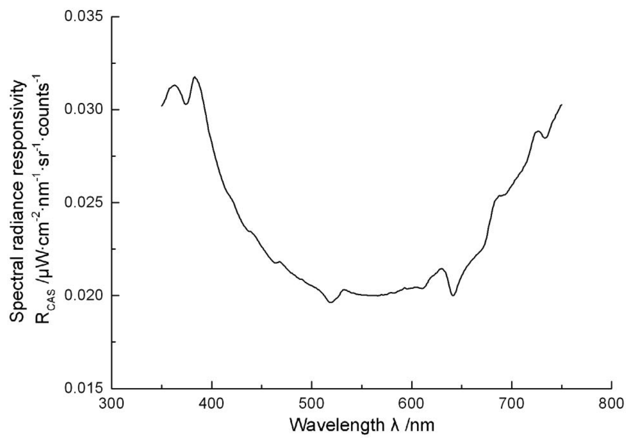

Fig. 3. Spectral radiance responsivity for CAS spectroradiometer.

factor for off-axis illumination including vignetting effects; $f(x, y)$ is the goniometric variation of the spectral irradiance standard over the projected area of the Gershun tube FOV of the CAS spectroradiometer on the plaques; BRDF is the average BRDF value of the Spectralon plaques in the Gershun tube FOV of a CAS spectroradiometer.

The spectral radiance responsivity $R_{\mathrm{CAS}}(\lambda)$ of the CAS spectroradiometer was obtained further by

$$R_{\mathrm{CAS}}(\lambda) = \frac{L_b(\lambda)}{S_b(\lambda)} = \frac{E_b(\lambda) \cdot f(\lambda)}{\pi \cdot S_b(\lambda)}, \tag{2}$$

where $L_b(\lambda)$ is the spectral radiance of Spectralon plaques to the direction of a CAS spectroradiometer; $E_b(\lambda)$ is the spectral irradiance of the NIST standard lamp at the position of Spectralon plaques; $f(\lambda)$ is the hemispherical reflectance of the Spectralon plaque;$S_b(\lambda)$ is the measured signal of the CAS spectroradiometer as viewing the Spectralon plaques.

The spectral radiance responsivity of the CAS spectroradiometer obtained after the spectral radiance calibration is shown in Fig. 3. Since the spectral radiance standard is established based on the spectral irradiance standard lamp and Spectralon plaques, compared to absolute detector-based calibration, the CAS spectroradiometer-based combined standard uncertainties in integrating sphere radiance should be relatively greater, as shown in Table 1.

After calibrated by the spectral radiance standard, the spectral radiance of the spectrally tunable radiant source can be expressed by

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

$$L_{mx}(\lambda) = R_{\mathrm{CAS}}(\lambda) \cdot S_{\mathrm{mx}}(\lambda), \tag{4}$$

$$L'_{0x}(\lambda) = \sum_{1}^{N} R_{\mathrm{CAS}}(\lambda) \cdot S_{\mathrm{mx}}(\lambda), \tag{5}$$

where $L_{0x}(\lambda)$ is the measured spectral radiance of the integrating sphere source in a spectrally tunable radiant source in broadband modes; $L_{\mathrm{mx}}(\lambda)$ is the measured spectral radiance of the integrating sphere source in a spectrally tunable radiant source in narrow-band modes;$L'_{0x}(\lambda)$ is the accumulated spectral radiance of $L_{mx}(\lambda)$ ($m = 1$ to N); $R_{\mathrm{CAS}}(\lambda)$ is the spectral radiance responsivity of the CAS spectroradiometer;$S_{0x}(\lambda)$ is the readings of the CAS spectroradiometer for the spectrally tunable radiant source in broadband modes; and $S_{\mathrm{mx}}(\lambda)$ is the readings of the CAS spectroradiometer for the spectrally tunable radiant source in narrow-band modes (m = 1 to N).

Figures 4(a) and 4(b) show the spectral radiance distribution of the spectrally tunable radiant source in two working modes. Figure 4(c) shows the relative spectral distribution of the supercontinuum fiber laser with the output power level 16% to 70%. The standard deviation ratio of $L'_{0x}(\lambda)$ the accumulated spectral radiance of $L_{\mathrm{mx}}(\lambda)$ (m = 1 to N) in narrow-band modes to $L_{0x}(\lambda)$ the measured spectral radiance of the integrating sphere source in spectrally tunable radiant source in broadband modes is less than 0.5%, as shown in Fig. 4(d).

Table 1. CAS Spectroradiometer-based Combined Standard Uncertainties in Integrating Sphere Radiance

The Uncertainty Component	Magnitude			
	250 nm	375 nm	500 nm	750 nm
Spectral irradiance for the 1000 W spectral irradiance standard FEL lamp	1.7%	1.25%	0.85%	0.7%
BRDF of the Spectralon plaques	4%	4%	4%	4%
Supercontinuum fiber laser (400 nm to 700 nm) or xenon lamp (250 nm to 750 nm) stability	0.3%	0.3%	0.3%	0.3%
DMD narrow-band to broadband	0.5%	0.5%	0.5%	0.5%
Long-term stability and reading of the CAS spectroradiometer	2%	2%	2%	2%
CAS spectroradiometer-based combined standard uncertainties in integrating sphere radiance	4.82%	4.68%	4.59%	4.56%

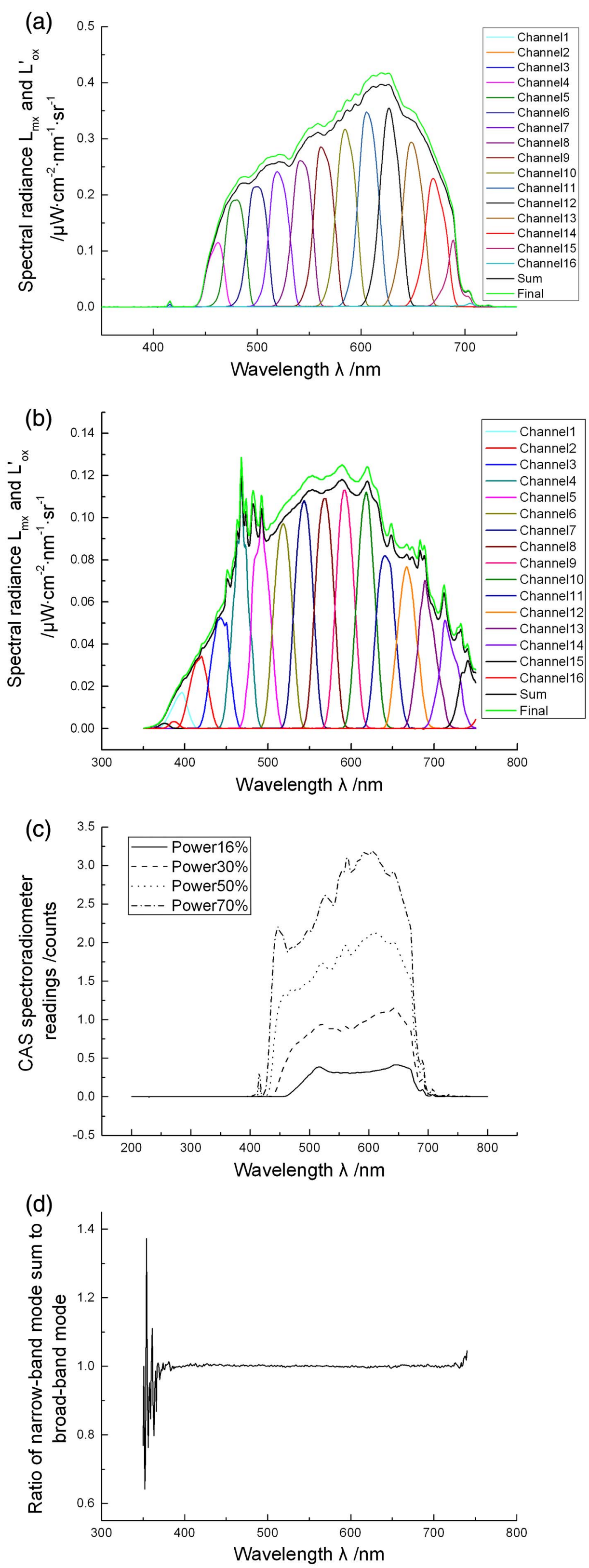

Fig. 4. Spectral radiance curves of the spectrally tunable radiant source in two working modes. **Channels 1–16** for narrow-band mode, **Sum** for broadband mode and **Final** for broadband mode corrected by Gershun tube radiometer (a) for the supercontinuum fiber laser and (b) for the xenon lamp. (c) CAS spectroradiometer readings for supercontinunm fiber laser in different power level. (d) The ratio of $L'_{0x}(\lambda)$ to $L_{0x}(\lambda)$.

B. Measurement and the Calibration Based on Detector Standard

A Gershun tube radiometer, specially designed and developed on the basis of Eppeldauer's important information [6], is used for the spectral radiance measurement and monitoring of the spectrally tunable radiant source. Figure 5(a) shows the structure of a Gershun tube radiometer, which consists of two precision apertures (front aperture $D = 11.8$ mm $\pm$ 3 μm and detector aperture $d = 6$ mm $\pm$ 3 μm) with certain spacing (spacing $s = 181.2$ mm $\pm$ 100 μm) and a Hamamatsu single planar silicon photodiode Model S2281, S/N31100. The baffle apertures and the black anodic oxidation process of the interior surface are used for reducing stray light. The spectral radiant power responsivity of S/N31100 is determined by comparisons to Hamamatsu silicon photodiode Model S2281, S/NI677 calibrated and issued by the National Institute of Standard and Technology with uncertainty 1.68% to 0.2% in 350 nm to 750 nm. The comparisons were carried out on the McPherson 209 monochromator-based spectral comparison equipment in our laboratory [7]. The uncertainty of the transference from S/N I677 spectral radiant power responsivity to S/N 31100 spectral radiant power responsivity is 0.4%, and the Gershun radiometer-based combined standard uncertainty in the integrating sphere radiance is 1.87% at 350 nm to 0.85% at 750 nm, as shown in Table 2.

Figure 5(b) shows the spectral radiant power responsivity of the S/N31100 silicon photodiode. The output of the Gershun

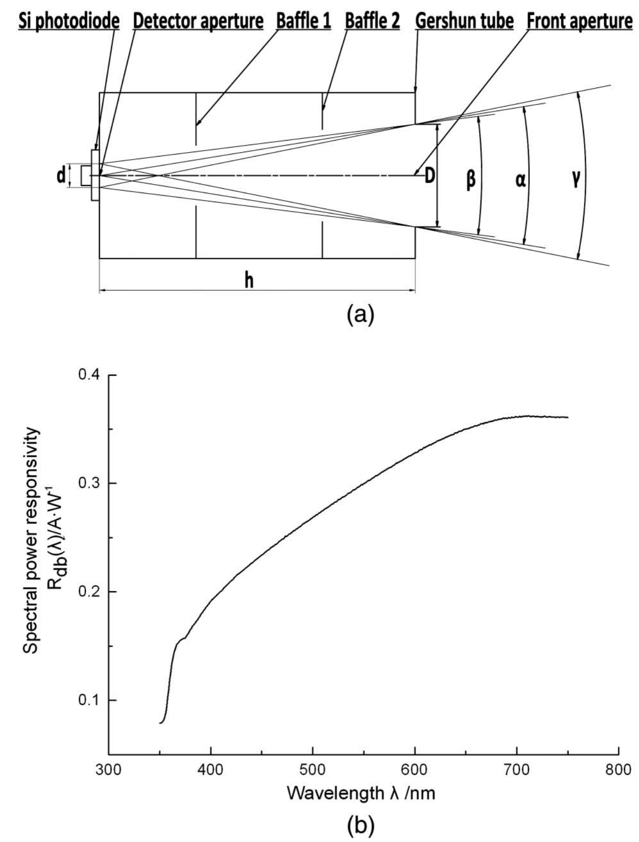

Fig. 5. (a) Structure of Gershun tube radiometer. (b) The spectral radiant power responsivity of S/N 31100 silicon photodiode absolute detector.

Table 2. Gershun Radiometer-based Combined Standard Uncertainties in Integrating Sphere Radiance

The Uncertainty Component	Magnitude			
	350 nm	400 nm	450 nm	500 nm to 750 nm
Spectral radiant power responsivity of Model 2281, S/N I677 silicon photodiode issued and calibrated by NIST	1.68%	1.46%	0.24%	0.22%
Uncertainty of the transference from S/N I677 spectral radiant power responsivity to S/N 31100 spectral radiant power responsivity	0.4%	0.4%	0.4%	0.4%
Long-term stability and the reading of the S/N 31100 silicon photodiode	0.3%	0.3%	0.3%	0.3%
Supercontinuum fiber laser (400 nm to 700 nm) or xenon lamp (250 nm to 750 nm) stability	0.3%	0.3%	0.3%	0.3%
DMD narrow-band to broadband	0.5%	0.5%	0.5%	0.5%
Diameters and the spacing for the precision apertures of Gershun radiometer	0.3%	0.3%	0.3%	0.3%
Gershun radiometer-based combined standard uncertainties in integrating sphere radiance	1.87%	1.68%	0.86%	0.85%

tube radiometer is fed to a 6517A electrometer and then to a computer through IEEE-488 interface for data acquisition and processing. According to the measurement value and the monitoring value from the Gershun tube radiometer, the output of the integrating sphere source in the spectrally tunable radiant source in narrow-band modes is adjusted through a DMD to compensate for the aging and the decay effect of the spectrally tunable radiant source system during the calibration course for remote sensing instruments, and therefore the spectral radiance of the radiant source system in broadband modes is kept stable.

The output of the Gershun tube radiometer can be expressed [6] as

$$\Delta S_{dm}(\lambda) = \eta_m \cdot R_{db}(\lambda) \cdot L_{mx}(\lambda) \cdot \omega_g \cdot A_d, \tag{6}$$

where $R_{db}(\lambda)$ is the spectral radiant power responsivity of the silicon photodiode for the Gershuntube radiometer; $L_{mx}(\lambda)$ is the spectral radiance of the mth spectral channel of the spectrally tunable radiant source in narrow-band modes ($m = 1$ to N); ω_g is the viewing solid angle for the Gershun radiometer; A_d is the area of the detector aperture for the Gershun radiometer; and η_m is the modifying coefficient, considering the equation is unequal because of the uncertainty of the measurement value $\Delta S_{dm}(\lambda)$ and the uncertainty of the calculated value $R_{db}(\lambda).L_{mx}(\lambda).\omega_g.A_d$.

After the summations from 350 nm to 750 nm with an increment of 0.1 nm instead of the integration of formula (6), the total output of the Gershun radiometer for the mth spectral channel of the spectrally tunable radiant source in narrow-band modes is

$$S'_{dm} = \int R_{db}(\lambda) L_{mx}(\lambda) \varpi_g A_d \mathrm{d}\lambda, \tag{7}$$

$$S_{dm} = \eta_m \int R_{db}(\lambda) L_{mx}(\lambda) \varpi_g A_d d\lambda = \eta_m \cdot S'_{dm}. \tag{8}$$

Table 3, and Figs. 6(a) and 6(b) show the measurement value of the Gershun tube radiometer S_{dm}, the calculation value of the Gershun tube radiometer S'_{dm}, and the η_m. From Table 3, and Figs. 6(a) and 6(b), we can see the η_m is almost a constant and the STDEV of η_m is 1.1% and 0.75% for 16 spectral channels. This means the measurement based on the absolute detector and based on standard lamp are identical and consistent, although they root in a different primary standard. Since the uncertainty of the spectral calibration based on the spectral radiation standard source is greater than that based

Table 3. Typical Ratio η_m of the Integrated Value to the Measured Value for Gershun Tube Radiometer

Spectral Channel	Supercontinuum Fiber Laser			Xenon Lamp		
	Integrated S'_{dm}	Measured S_{dm}	η_m	Integrated S'_{dm}	Measured S_{dm}	η_m
1	0.109537354	0.113292265	1.034279732	/	/	/
2	0.114663209	0.119608265	1.043126785	0.064559153	0.06906838	1.069846439
3	0.169559302	0.178261425	1.051322002	0.16618406	0.1760155	1.059159948
4	0.98355799	1.032472625	1.049732335	0.295668118	0.31405644	1.062192442
5	1.893296776	1.991094025	1.051654474	0.532272595	0.56547814	1.062384473
6	2.265819826	2.354345025	1.039069832	0.593020704	0.62616966	1.055898481
7	2.614940151	2.794503025	1.068668063	0.651818218	0.68350668	1.048615489
8	3.025228292	3.179903025	1.051128285	0.761892866	0.8012835	1.051701015
9	3.416913144	3.605281025	1.055128086	0.81987206	0.86727954	1.057823021
10	3.892660505	4.071583025	1.04596407	0.86395045	0.91131268	1.05482054
11	4.492887351	4.694721025	1.044922932	0.8761293	0.9185885	1.048462253
12	4.679544988	4.883113025	1.043501673	0.727775081	0.77089934	1.059254926
13	4.157220404	4.384289025	1.054620299	0.684983064	0.7226083	1.054928709
14	3.29939869	3.466183025	1.050549919	0.582598644	0.61629956	1.057845854
15	1.132777775	1.192467625	1.052693345	/	/	/
16	0.156044879	0.168562425	1.080217603	/	/	/
STDEV			1.1%			0.75%

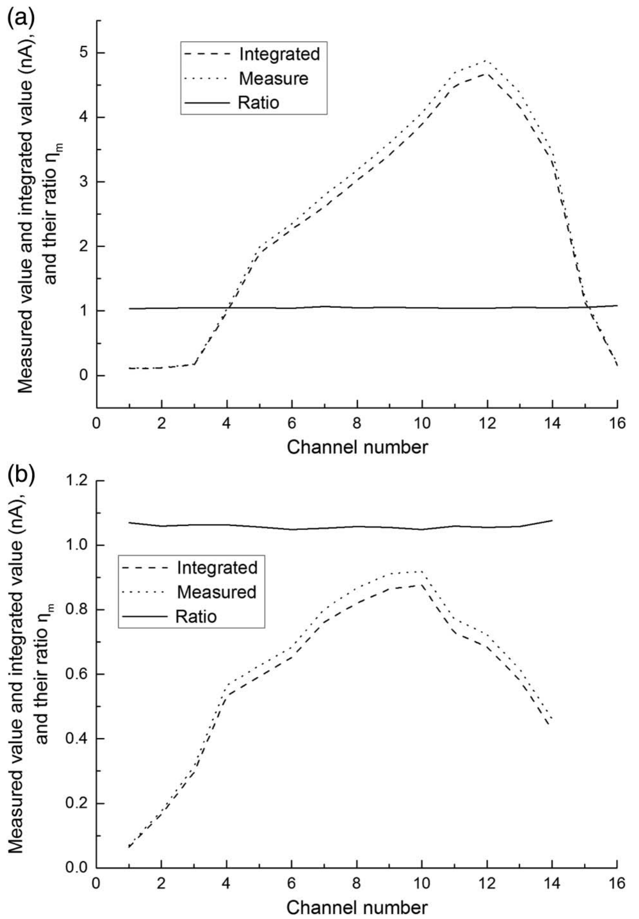

Fig. 6. Integrated value and the measured value for Gershun tube radiometer, and their ratio η_m (a) for the supercontinuum fiber laser and (b) for xenon lamp.

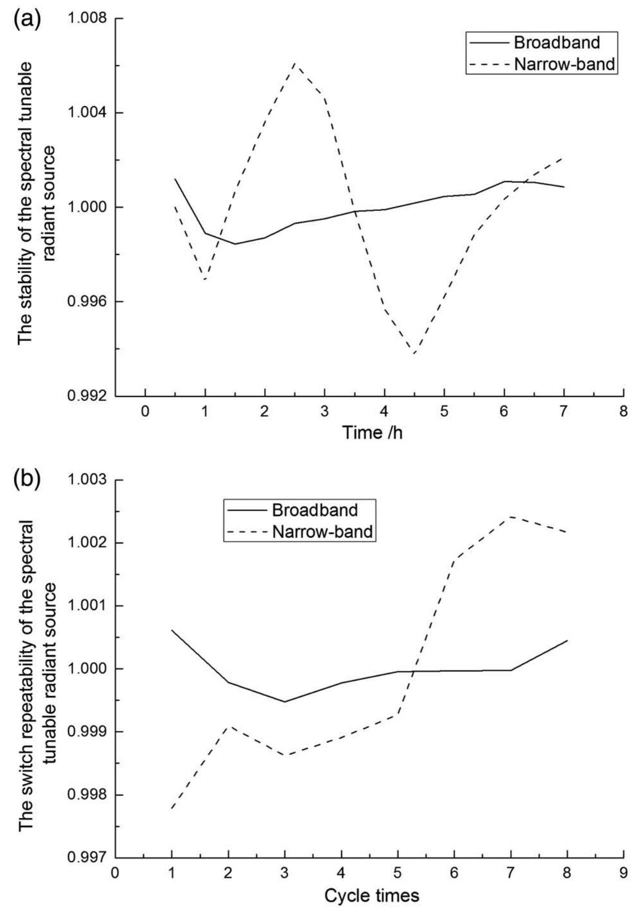

Fig. 7. (a) Stability of spectrally tunable radiant source in narrow-band mode (channel 8) and broadband mode during 7 h. (b) The switch repeatability of spectrally tunable radiant source in narrow-band mode (channel 8) and broadband mode during eight cycles.

on the absolute detector, the η_m is used to modify the calibration results based on a standard lamp, to represent the spectral radiance of this spectrally tunable radiant source and to estimate the uncertainty of the calibration.

The absolute spectral radiance of the spectrally tunable radiant source in broadband modes can be expressed as

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

From formula (9), the absolute spectral radiance of the spectrally tunable radiant source in broadband modes is shown by the "Final" curve of Figs. 4(a) and 4(b), and the uncertainty of the absolute spectra radiance is 1.87% at 350 nm to 0.85% at 750 nm.

C. Stability and Repeatability of the Spectrally Tunable Radiant Source

The stability and the switch repeatability of the spectrally tunable radiant source were measured by the Gershun tube radiometer in narrow-band modes and broadband mode after 20 min of preheating. The stability is better than ±0.3% within 1 h and the long-term stability is better than ±0.6% within 7 h, as shown in Fig. 7(a). The switch repeatability of the spectrally tunable radiant source is better than ±0.3%, as shown in Fig. 7(b). The preheating time for every switch on is 20 min.

4. CONCLUSION

A high-brightness spectrally tunable radiant source using supercontinuum fiber laser and DMD has been developed. The spectral radiance is about 20 times higher than the spectrally tunable radiant source using a 300 W super quiet xenon lamp. The stability is better than ±0.3%/h. The uncertainty of the spectral radiance of the spectrally tunable radiant source is less than 1.87% at 350 nm to 0.85% at 750 nm, based on the absolute detector monitoring and calibrating.

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