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Optical system design of solar radiation observation instrument

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Abstract: In order to realize the sunlight observation with each wavelength, aiming at the narrow spectrum test range and low spectral resolution weakness of solar radiation observation instrument, the optical system design scheme was proposed which can realize nanometer resolution based on applying spectral measurement technology. Combining with the characteristics of the sunlight and the service environment of the solar radiation observation instrument, the collecting light system was designed basing on fiber and cosine corrector. According to spectral range and spectral resolution, the spliting light system was designed with multi-channel and manometer resolution. Experimental and design results indicate that the spectral resolution precedes 20 nm and realizes the sunlight observation. It can satisfy the instrument requirements of wide spectrum and nanometer resolution.

Key words: solar radiation observation; optical system design; wide spectrum; resolution
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光谱型太阳辐射观测仪光学系统设计

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摘 要:为了实现太阳光各波长下观测,针对现有的太阳辐射观测仪光谱测试范围窄、光谱分辨率低的缺点,提出了一种运用光谱测量技术实现高分辨率太阳观测仪光学系统的设计方案。结合太阳辐射观测仪的使用环境与太阳光的特点,利用光纤、余弦校正器等器件设计了太阳辐射观测仪的收光系统。根据太阳光的光谱范围以及光谱分辨率的要求,设计了多通道、高分辨率的太阳辐射观测仪分光系统。实验与设计结果表明:光谱分辨率优于 20 nm,能够实现太阳的光谱观测。满足太阳辐射观测仪宽光谱、纳米分辨率等要求。

关键词:太阳辐射观测; 光学系统设计; 宽光谱; 分辨率

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0 Introduction

Solar radiation is the main energy source of the earth, and is closely related to the spectral distribution. After the solar radiation goes through the atmosphere, the selective absorption and scattering of atmosphere affect the global climate change, so how to effectively assess the solar radiation information will contribute to the development of meteorological observation, environmental monitoring and the application field of solar energy[1-2].

In China, a photoelectric conversion technology has been developed to realize multi band solar radiation, based on diode array detector and the linear array CCD detector. However, as the instrument is used mainly for the measurement of biological samples, it did not fully realize the full band measurement of the solar spectral radiation signal. In addition, it is unable to run the ultraviolet and infrared test. In recent years, the production of spectral radiation instruments in the USA, Japan, France and other countries has become series. The spectral range covers from the UV to the IR band, but it did not realize one observation instrument form 300-2 500 nm [3]. The development of solar energy industry, climate change and other environmental changes has put forward the request to the solar meticulous observation, so 300-2 500 nm solar spectral high resolution detection has become the research focus. This paper uses the environment of solar radiation observation and the solar spectral range as the design basis, adopting the method of array detector, realizing the solar spectrum meticulous observation, designing the light collecting system and the light scattering system, and finally proves the feasibility of the optical system design with the design results and actual test curves.

1 Solar radiation observation instrument

1.1 Components and working principle

The solar radiation observation instrument is a special equipment used to measure the solar radiation spectral distribution and solar spectral energy distribution. It can measure direct solar radiation, the solar diffuse, ground reflection, total solar radiation and so on. It is the effective method to obtain the spectral characteristics of solar radiation. The main important structuring components include the light collecting system and the light scattering system, data controlling and processing system, and mechanical system, as shown in Fig.1.

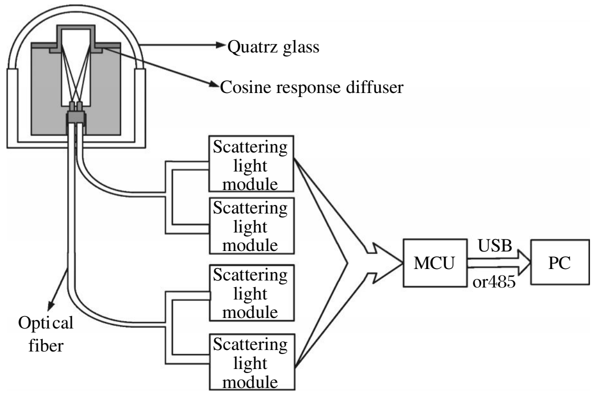


Fig.1 Components of the solar spectral radiation observation instrument

As shown in Fig.1, the sun shines through the quartz glass cover into the cosine response diffuser, then shines through the cosine response diffuser into the optical fiber, and then into each module the detector collect data, finally it processes data via the MCU, and obtains the observation information of the full sun spectrum. At the same time, the solar spectrum is 300-2 500 nm. Due to the response band detector limit, we observe the sunlight by dividing it to four bands, respectively 250-430 nm, 400-1 000 nm, 900-1 700 nm, 1 500-2 500 nm.

1.2 Main technical indexes

This topic comes from the R&D Special Fund for Public Welfare Industry "***radiation instrument development and application test". The main technical indicators are shown in Tab.1.

Tab.1 Main technical indicators

Number	Technical index	Reference number
1	Scope of spectrum	300-2 500 nm
2	Resolution	<20 nm

2 Light collecting system design

2.1 Quartz glass

Solar radiation observation instrument will be used in outdoor test in a long term to complete observation of solar irradiance of wave length at different time of each day. In order to ensure the service life and performance of optical devices and to prevent dust and moisture get into the solar radiation observation instrument which could impact the detection, glass cover is used to protect the optical devices. At the same time, because of the wide spectrum including ultraviolet, visible and infrared, the glass cover should be able to enable all of the light 300−2 500 nm band to pass through the glass cover. Quartz is the best one among all ultraviolet permeable materials, and it has the advantages of high temperature resistance, minimal coefficient of thermal expansion, characteristics of good chemical stability. JGS2 in 200–2 500 nm wavelength range without absorption band; in 2 600−2 800 nm band it has a strong absorption band, which could meet the practical requirements of radiation observation instrument[4].

2.2 Cosine response diffuser

Solar radiation observation instrument light collecting system is mainly used to collect solar radiation effectively. The realization of effective testing of the solar radiation depends on the light direction and radiation uniformity, therefore, for the irradiance detection, detectors required to receive light with a cosine response characteristics, eliminate the impact of radiation light angle. The cosine response diffuser is a tubular structure, with one end placed diffuse transmission plate, as shown in Fig.2[5].

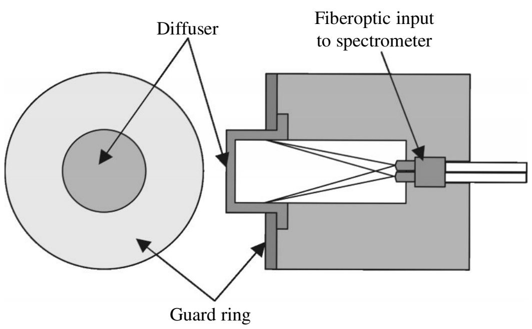


Fig.2 Cosine response diffuser and the optical fiber coupling diagram

After going through the diffuse transmission disc, the radiation light has similar characteristics to the cosine radiation, i.e. all directions light after the cosine response diffuser have the same brightness, the luminous intensity and vertical directions the light intensity are of cosine relationship, as shown in formula(1).

$$I_i = I_0 \cos i \qquad (1)$$

Where I_0 is the luminescence intensity of light−emitting surface normal direction. I_i is the luminous intensity in angle i.

After the sunlight goes through the cosine response diffuser, the cosine curve is not standard. Relative cosine error and diffuse cosine error exist. The so−called relative cosine error refers to in a certain angle, the ratio between solar irradiance ideal value and the measured value, as shown in formula(2).

$$\psi_\theta = \frac{E_{\text{measured}}}{E_{\text{ideal}}} = \frac{E(\theta)_{\text{measured}}}{E_0 \cdot \cos\theta} \qquad (2)$$

Where θ in the formula is the incident angle (°). E_0 is the radiation normal direction(W/m^2). ψ_θ is the relative cosine error correction.

Diffuse cosine error(DCE) reflects the actual quality of cosine response, defined as shown in formula(3).

$$DCE = \frac{\sum_{-\pi/2}^{\pi/2} \left|(\psi_\theta - 1)\sin\theta\cos\theta\right|}{\sum_{-\pi/2}^{\pi/2} \left|\sin\theta\cos\theta\right|} \cdot 100\% \qquad (3)$$

In the ideal condition, DCE is 0. If $DCE \neq 0$, it is expressed as a percentage of the ideal cosine response error. Using a solar constant (1 353 W/m^2)of solar simulator to test its diffuse error, the incident angle is −π/2−π/2. The test results are normalized as shown in Fig.3, the error is shown in Fig.4.

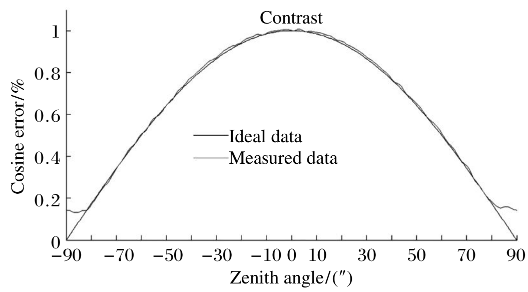


Fig.3 Cosine response curves

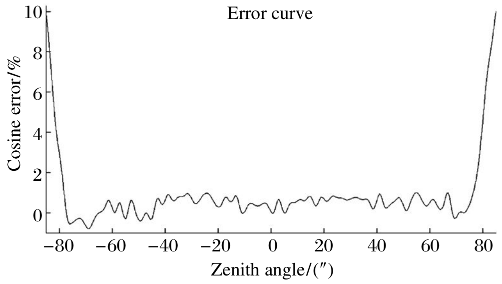


Fig.4 Diffuse cosine error curve

2.3 Optical fiber

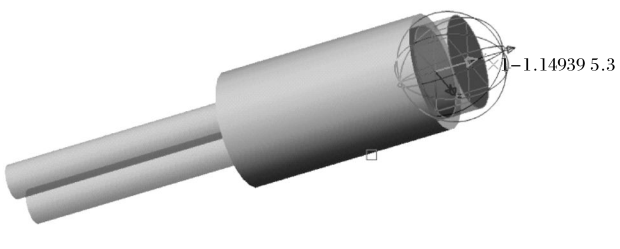
Optical fiber is used for solar radiation conduction, and solar radiation is transferred to the four light paths. Currently, no fiber can achieve 300 −2 500 nm light transmission, so the solar radiation, after going through the cosine response diffuser, is divided into two paths−one path with two optical fibers which can transfer 200 nm to 1 100 nm, while the other light path using 2 optical fibers which can transfer 400−2 500 nm, as shown in Fig.1[6].

2.4 Analysis of light collecting system simulation

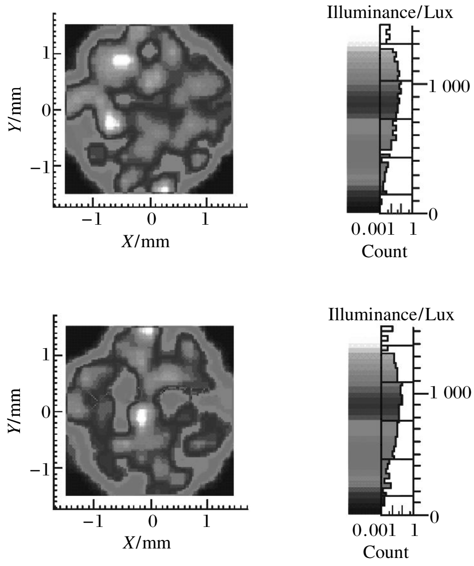
The solar radiation observation instrument includes quartz glass, cosine response diffuser and optical fiber. The cause of the energy attenuation include quartz glass and diffuse transmission device producing energy loss, the light importing the fiber and the light transmitting in the fiber.

The energy loss by the quartz glass and diffuse transmission device producing energy loss and the light transmitting in the fiber can reflect the device itself, in order to reflect transmissivity of the light importing the fiber, using lighttools software simulate as shown in Fig.5.

As shown in Fig.5(b), radiation energy loss is 90%, and the light collecting system transmissivity is 4.8%. The sun radiation through the atmosphere, in sunny day, ground irradiance of 1 000 W/m^2, After solar radiation observation instrument the irradiance is 48 W/m^2 (4.8×10^{-3} W/cm^2), compared with the detector sensitivity index, the design can satisfy the requirement of the detector.



(a) Optical modeling



(b) Receiving energy in optical fiber incident

Fig.5 Simulation results

3 Light scattering system design

The light scattering system of the solar radiation observation instrument is similar to the optical System of the grating spectrograph, including Crossed Czerny − Turner structure, Concave Holographic Grating structure and Axial Transmissive structure. Concave Holographic Grating structure is influenced by grating, the optical structure is fixed and can't optimize. Axial Transmissive structure is too large to realize miniaturization. So this design adopts Crossed Czerny −Turner structure, the structure is shown in Fig.6, including grating, collimating lens, imaging lens and detector[7].

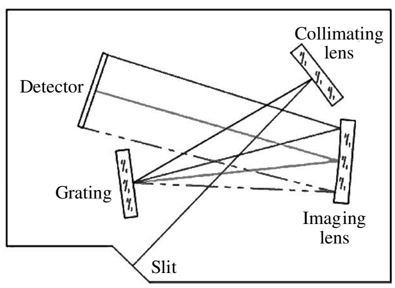


Fig.6 Crossed Czerny−Turner structure

3.1 Setting of the initial structure

The collimating system of the light scattering system of the solar radiation observation instrument need match dispersion system, the basic features of the dispersion system can play, and then the resolution of light scattering system can close to the resolution ability of the dispersion system.

3.1.1 Determine of the original design parameters

The original design parameters of the light scattering system include wavelength range, resolution, dispersion rate, focal length and D/f. Among them the dispersion rate represent angular dispersion and line dispersion, as shown in formula (4) and (5).

$$\frac{d\theta}{d\lambda}=\frac{m}{d\cos\theta} \tag{4}$$

$$\frac{dl}{d\lambda}=f\cdot\frac{d\theta}{d\lambda}=f\cdot\frac{m}{d\cos\theta} \tag{5}$$

Where d means grating constant, m means the order of diffraction, θ means diffraction angle. Represent grating constant and dispersion rate are inverse, if dispersion increase, separate two adjacent spectrum is easier. So choosing the gating has more grooves, the light scattering system distinguishes more clearly.

The spectral resolution of the solar radiation observation instrument is the distinguish ability at theoretical status. It means the ability of distinguishing two spectrum with small different wavelength. According to the rayleigh criterion, if distance is separated by dispersion, at same time one spectrum maximum coincide with the other adjacent spectrum minimum, two spectrum can be distinguished. So the spectral resolution of the solar radiation observation instrument is approximate to FWHM[8].

3.1.2 Calculation of aberration

The light scattering system of the solar radiation observation instrument is reflective collimation system. The reflective system can apply from UV to infrared, so it satisfies the design requirements. At the same time the reflection system has not color aberration, It is useful of the aberration correction, but the reflection system has center block, we need use off-axis system, in this way axis point become off-axis point, off-axis aberration increasing, Coma and astigmatism is the key of the optimization[9-10].

(1) Spherical aberration

The light through collim ating lens, spherical wave can′t become the ideal spherical wave, so the point become disc of confusion, the radius of the disc of confusion is defined d_r. Through two reflection, spherical aberration superimpose is caused, the value is shown in formula(6).

$$d_r=\frac{\sqrt{2}}{64}\frac{D^2}{f^2} \tag{6}$$

(2) Coma

Coma is related to the object point off-axis distance and aperture stop location. The size of disc of confusion is shown in formula(7) and (8).

$$L_e=\frac{3MD^2\omega}{16f} \tag{7}$$

$$W_e=\frac{MD^2\omega}{8f} \tag{8}$$

(3) Astigmatism

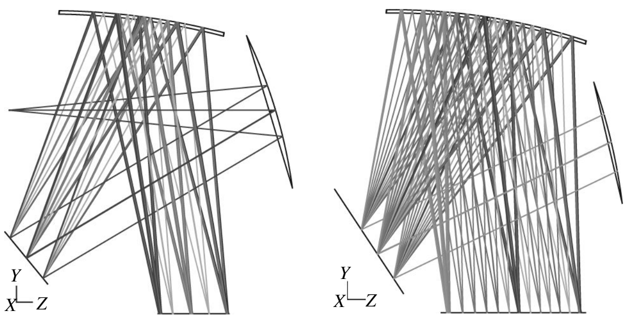
Astigmatism is related to aperture stop and field. The size of astigmatism is shown in formula(9).

$$L_A=M^2D\sin^2\omega \tag{9}$$

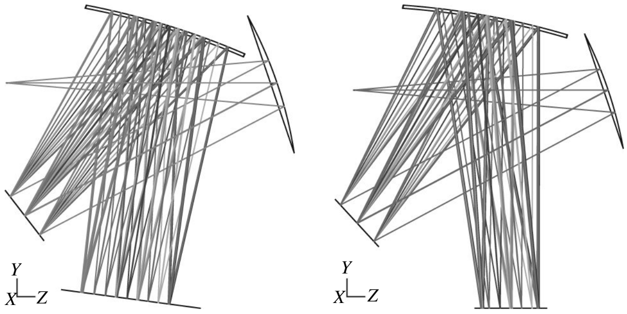
3.2 Results of light scattering system

Due to the limit of detector spectral range and spectral resolution, in order to realize the spectral range from 300 nm to 2 500 nm and high-resolution detection, this paper adopts four spectrum detection module to detect different wavelengths range of solar radiation energy. Four spectrum detection module is include 250-430 nm, 400-1 000 nm, 900-1 700 nm, 1 500-2 500 nm, the design results are shown in Fig.7.

As Fig.8 shown, the spectral resolution of four spectrum detection module iare 3 nm, 5 nm, 7 nm and 20 nm, It satisfies the design requirements of better than 20 nm.

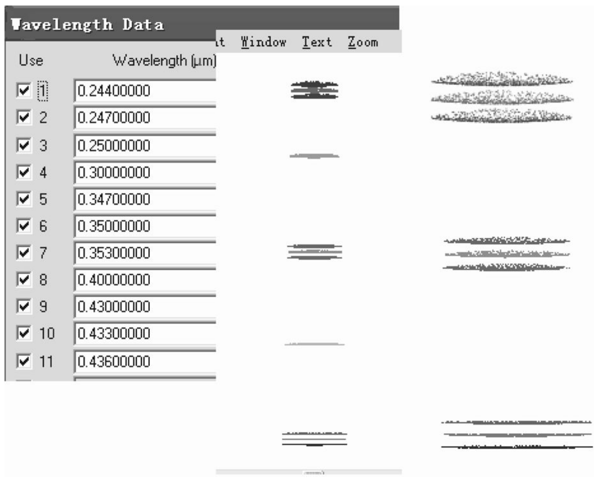


(a) 250-430 nm　　(b) 400-1 000 nm

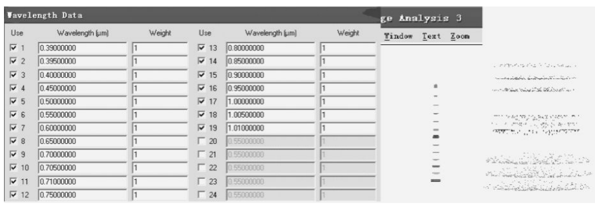


(c) 900–1 700 nm (d) 1 500–2 500 nm

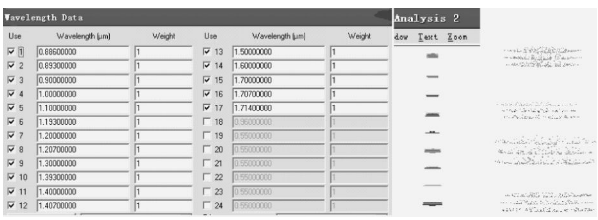
Fig.7 Light scattering system design



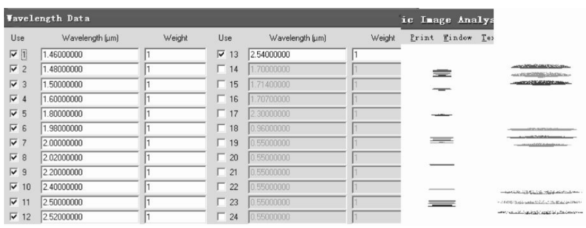
(a) 250–430 nm



(b) 400–1000 nm



(c) 900–1 700 nm



(d) 1 500–2 500 nm spectral resolution results

Fig.8 Spectral resolution results

4 Test result

Finally, the design result of the light collecting system and the light scattering system reflect the accuracy of solar radiation observation at the different time and different weather. Because of the solar spectrum is changing at the different time and different weather, using the solar radiation observation instrument has tested solar spectrum at four kinds of environment , including sunny noon, sunny morning, cloudy noon and cloudy morning. The four test curves contrast AM1.5 solar spectral irradiance standard curve, the test curve is shown in Fig.9. As Fig.9 shown, the design can test spectrum from 300–2 500 nm, the test curve matches the AM1.5 curve.

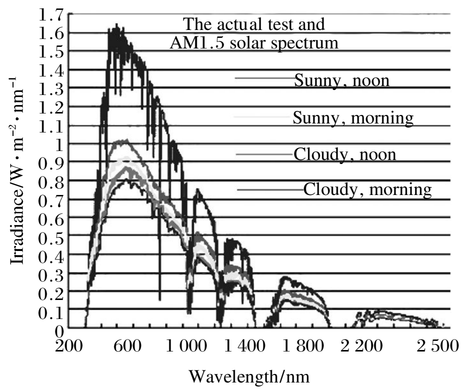


Fig.9 Solar spectrum curves with actual test

5 Conclusion

In this paper, design basis is the technical indicators of solar radiation observation instrument. Design features is realizing high resolution observation from 300 nm to 2 500 nm, The core is the light collecting system design and the light scattering system design. This paper has completed the optical system design of solar radiation observation instrument. This paper has analyzed the selection method of the quartz glass, cosine corrector diffusers and the fiber, and has got the transmittance of the light collecting system using the lighttools, at the same time has designed the light scattering system and evaluated the resolution with every waveband. The design results show that four spectral system can achieve the design requirements of the wave resolution better than

20 nm. The practical test results show that the solar radiation observation instrument can realize the solar radiation light observation from 300 nm to 2 500 nm at the different time and different weather.

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