1*　　　　1　　　1　　　1　　　2

（1.　　　　　　　　　　　　　　　　　　　130033;

2.　　　　　　　　　　　　　　130000）

:　　　　　　　170 ~ 380 nm　　　　　　　　　　± 0. 02 nm
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。　　　　　　± 2 μm　　　　　　　　　　　　　　　　。

　　　　　　　　　　　　。　　　　　　　　　　　－ 0. 005 ~ + 0. 007 nm

± 0. 02 nm　　　　　　。

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Structure design and wavelength accuracy analysis of ultraviolet double grating spectrometer

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Abstract: In order to observe the solar spectrum between 170 nm to 380 nm precisely, an ultraviolet double grating spectrometer with its wavelength repeatability accuracy better than ± 0. 02 nm has been designed. A wavelength scanning mechanism is the key module of the ultraviolet double grating spectrometer. Mechanical parameters are derived from optical parameters according to the grating dispersion principle. Error sources which influence the spectrometer wavelength repeatability error have been analyzed. According to the analysis results, the repeatability error of the lead screw is the main error source. A wavelength scanning mechanism has been assembled with a ± 2 μm accuracy lead screw, and the spectrometer mechanism structure has been designed. Experiments have been carried out with a mercury lamp as light source to verify wavelength repeat-

ability. The experiment results show that the wavelength repeatability of the spectrometer is between -0.005 nm and $+0.007$ nm which is better than the required accuracy of ± 0.02 nm.

Key words: double grating spectrometer; wavelength scanning mechanism; wavelength repeatability; concave grating; error analysis

1

Introduction

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[1-7]
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[3 8]
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Solar radiation continuously provides the Earth with an external source of energy and solar energy fluctuation has a remarkable impact on Earth´s climate change weather environmental anomaly *etc*. Therefore the development of specialized instruments for long-term accurate monitoring of solar irradiance has important research value for geoscience [1-7] . Accurate measurement of solar spectral radiation also plays an active role in other disciplines involving the improvement trace gas inversion accuracy *etc* [3 8] .

[7] 。

170 ~ 380 nm

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[8-10 12-15]

。   CCD

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[8 10-13]

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Solar radiation energy has wavelength dependence and the majority of solar radiation energy is concentrated at visible light and near-infrared bands but the variation of solar radiation energy is stable within solar cycles. The proportion of energy at ultraviolet band is not high but the energy changes greatly within solar cycles and its variation may have a remarkable impact on the Earth´s atmosphere composition and climate [7] . The ultraviolet double grating spectrometer designed in this paper is an instrument intended for accurate monitoring of solar radiation at ultraviolet $170-380$ nm band. In order to reach the linear relationship between wavelength increment and control input such spectrometer generally uses a sine mechanism as the wavelength scanning mechanism [8-10 12-15] ; *i. e.* the sine of the pendulum rod´s rotation angle has linear relationship with the wavelength. In comparison with the spectrometer using plane grating and CCD the scanning type grating spectrometer has higher spectral resolution and simple and compact structure and achieves miniaturization more easily. The wavelength repeatability accuracy of the scanning type spectrometer depends on the accuracy of the wavelength scanning mechanism. At present typical wavelength scanning mechanisms include the forms such as cam lead screw *etc* [8 10-13] . The cam-based wavelength scanning mechanism cannot meet the requirements of the spectrometer designed in this paper due to the factors such as cam´s profile accuracy and volume *etc*. Thus a lead screw pendulum rod mechanism is used

as the wavelength scanning mechanism of the double grating spectrometer in is paper.

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According to the concave grating dispersion principle and spectrometer structure features con-version formulas from optical indexes to spectrometer structure parameters have been derived in this pa-per. In addition the scanning mechanism design has been improved on the basis of the traditional wavelength scanning mechanism based on lead screw pendulum rod. The zero positioning accuracy of the improved scanning mechanism has been improved and the driving force variation is more uniform in the whole scanning process. Error sources affecting wavelength repeatability accuracy have been ana-lyzed and the wavelength repeatability of the spec-trometer has been measured using a mercury lamp as the light source so as to verify the correctness of the-oretical analysis and the realizability of the index.

2

Operating principle and structure design of the spectrometer

2. 1

Concave grating dispersion principle and sine mechanism principle

                      1   。

N   B

        i θ 2δ

                φ B

N   。

The concave grating dispersion principle is

shown in Fig. 1. Similar to a plane grating N is the normal of the concave grating B is the angular bi-sector of incident light and diffraction light i is inci-dence angle θ is diffraction angle 2δ is the includ-ed angle between incident light and diffraction light and φ is the included angle between angular bisector B and normal N.
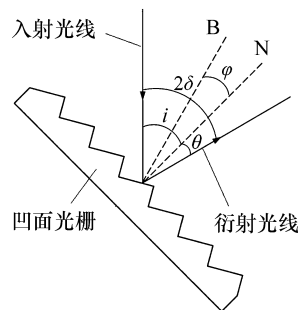

Fig. 1   Grating dispersion principle

                       [10-13]   :

The following formula is obtained from the dif-fraction grating dispersion formula [10-13] :

$$\sin i - \sin\theta = \frac{m\lambda}{d} \qquad (1)$$

m d λ

                      $m = 1$ $d =$ 1 /3600 mm。

Where m is grating diffraction order d is grating constant and λ is system scanning wavelength; for the spectrometer system in this paper $m = 1$ and $d = 1/3\ 600$ mm.

             1   :

The following formula can be obtained from the geometrical relationship between the included angles in Fig. 1:

$$\begin{cases} i = \delta + \varphi \\ \theta = \delta - \varphi \end{cases} . \qquad (2)$$

    (2)   (1)   :

Substitute formula (2) into formula (1) and carry out simplification to obtain:

$$\lambda = \frac{2d\sin\varphi\cos\delta}{m} . \qquad (3)$$

（3） d

2δ

                    φ

                              。

                    2   。

                              。

                              。

In formula （3） the grating constant d the included angle 2δ between incident light and diffraction light and grating diffraction order all are a constant so the linear relationship between control input and wavelength can be guaranteed as long as the relation of wavelength and sine of angle φ is linear. The schematic diagram of the sine mechanism used in wavelength scanning is shown in Fig. 2. The outer circle of the grating seat support bearing is fixed on the spectrometer cabinet wall and the inner circle is fixed with the grating shaft and pendulum tail end so that the pendulum rod can drive the grating to rotate. The other end of the pendulum rod keeps tight contact with the sliding block depending upon the spring tension. Driven by the stepper motor the lead screw rotates and the sliding block moves back and forth so that the pendulum rod drives the grating to rotate and wavelength scanning is achieved.
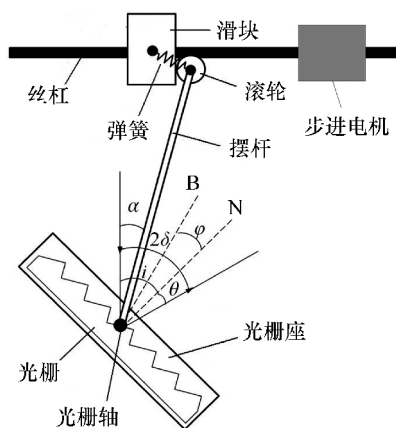

滑块
丝杠   滚轮
弹簧   步进电机
        摆杆
            B
        α N
        2δ φ
            i θ
                        光栅座
光栅
    光栅轴

2

Fig. 2   Wavelength scanning mechanism

                    170 ~ 380 nm
        18. 924 4° ~ 46. 464 8°
140 mm   75. 27 mm。

The scanning band of the spectrometer in this paper is 170 – 380 nm the corresponding grating rotation angle is 18. 924 4° – 46. 464 8° the pendulum rod length is 140 mm and the effective travel of the lead screw is 75. 27 mm.

                              N
            B
  。

  α N   B φ 。
                    :

For the well-adjusted spectrometer structure the normal N of the grating rotates with grating rotation and the position of the angular bisector is fixed. Therefore if the pendulum rod is vertical to the lead screw initially in the sine mechanism design the rotation angel α of the pendulum rod is always equal to the included angle φ between normal N and angular bisector B during grating rotation. The following formula can be obtained from the geometrical relationship:

$$\sin\varphi = \sin\alpha = \frac{x}{l} \qquad (4)$$

  x l
  。   （4）   （3）   :

Where x is the distance from the sliding block to the initial position and l is the pendulum rod length. Substitute formula （4） into formula （3） to obtain:

$$\lambda = \frac{2xd\cos\delta}{ml} . \qquad (5)$$

  （5） x

                              。

                              。

According to formula （5） except the sliding block position variable x all other parameters are a constant. The sliding block position is of linear rela-

tionship with the step number of the stepper motor so the wavelength position also has linear relation-ship with the input step number of the stepper motor. The control relationship has been simplified via the sine mechanism thus ensuring the improvement of the wavelength scanning accuracy and the reliability of the mechanism.

2. 2

Spectrometer structure design

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170～380 nm 。

The basic structure of the ultraviolet double grating spectrometer is shown in Fig. 3. The ultraviolet double grating spectrometer consists mainly of entrance slit component gratings intermediate slit component reflectors exit slit component detector *etc*. The light shield is at the foremost end of the system and plays a role in reducing stray light. Rays pass through the light shield quartz window diffuse transmission panel and entrance slit successively for dispersion on the first grating; refracted by the reflector rays pass through the intermediate slit; after passing through the second reflector and grating rays converge at the exit slit and finally reach the detector for data acquisition and processing. The parameters of the two concave gratings are completely identical and they are installed in the same grating seat to rotate co-axially. During spectrometer working the wavelength scanning mechanism drives the grating to rotate; at different rotation angles the detector receives the energy of lights with different

wavelengths and the mechanism performs continuous scanning so as to achieve continuous spectral measurement within the band range of 170 – 380 nm.
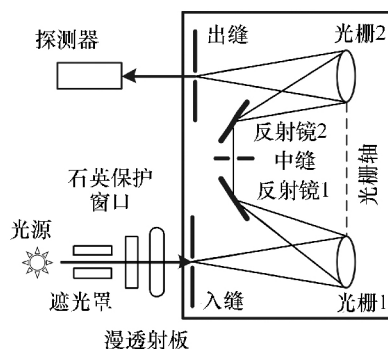

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Fig. 3　Schematic view of ultraviolet double grating spectrometer

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According to the operating principle of the ultraviolet double grating spectrometer the wavelength scanning mechanism is the key mechanism of the spectrometer and the reasonableness of the mechanism design has a decisive impact on wavelength repeatability accuracy. The lead screw mechanism has been improved on the basis of the traditional scanning mechanism based on lead screw pendulum rod

in this paper. In order that the roller can tightly con-tact the sliding block in the whole scanning process the fixed end of the pre-loaded spring is moved from the cabinet onto the sliding block as shown in Fig. 4. In the scheme where the fixed end of the spring is fixed on the cabinet wall the fixed end of the spring keeps still in the whole scanning process; as the travel of the sliding block increases the spring length increases remarkably and the needed driving torque of the stepper motor also increases ac-cordingly. In the new scheme the fixed end of the spring is fixed on the sliding block the spring also plays a role in pre-tightening and the spring size can be reduced remarkably. In the whole scanning process the variation of the spring tension is very small the friction between the roller and the sliding block is rolling friction and the driving torque of the stepper motor almost remains unchanged. This scheme can effectively reduce the required motor torque and also has remarkable advantages in reduc-ing spring amplitude during instrument vibration.
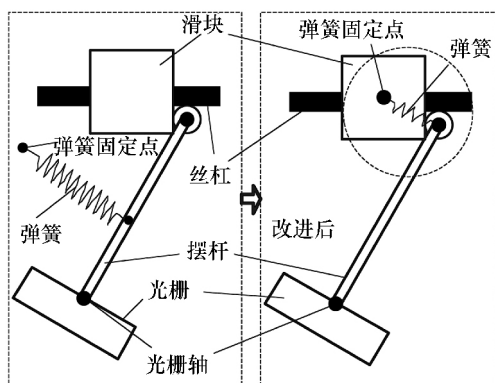

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Fig. 4　Diagram of improvemental spring design

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In order to improve the zero returning positio-ning accuracy of the wavelength scanning mecha-nism the method of combining rough positioning with precise positioning is used in zero positioning as shown in Fig. 5. The rough positioning sensor is installed on the sliding block to make linear motion and quickly search zero position; the precise positio-ning sensor is installed on the coupling and rotates with motor rotation. During zero position searching operation the motor rotates reversely at quick speed and reaches the rough positioning sensor position; then the motor rotates positively at slow speed and finds the precise positioning sensor position. The motor always rotates positively in the whole scanning process which can thus effectively reduce the lead screw backlash error and improve repeatability accu-racy.
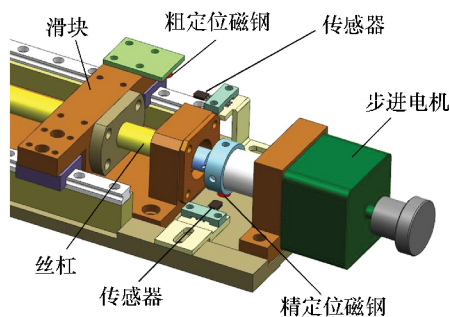

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Fig. 5　Rough and precise positioning method

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0. 4 mm × 1 mm。

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The structure of the whole spectrometer is shown in Fig. 6. In order to ensure the rigidity of the whole spectrometer structure the housing of the spectrometer uses the integral machining mode and

different components are partitioned with rib plates which can reduce the impact of stray lights on the system while increasing the rigidity. The three slit components are sliced from stainless steel sheets. The slit size is adjusted and tested under a 50-power microscope and the size of all the three slits is 0. 4 mm × 1 mm. The detector uses photomultipliers and is tightly installed with the exit slit component to prevent stray lights from entering.

波长扫描机构
中缝
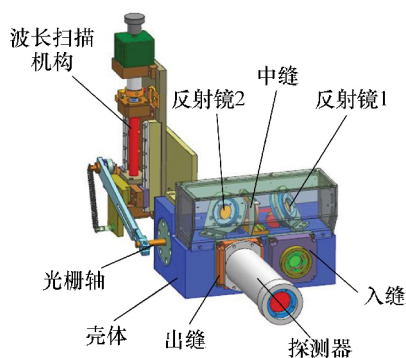反射镜2
反射镜1
光栅轴
入缝
壳体
出缝
探测器

6

Fig. 6 Structure diagram of spectrometer model

3

Wavelength repeatability error analysis

170 ~ 380 nm

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1 nm ±0. 02 nm。

High wavelength repeatability accuracy is the basic requirement satisfied to achieve accurate scanning within the solar spectral band range of 170 – 380 nm using the spectrometer and also the premise for subsequent linear calibration of wavelength and spectral measurement. Spectral resolution is decided

by the width of the entrance slit and exit slit. The smaller the width the higher the spectral resolution; but the energy entering the spectrometer system will also be reduce so as to reduce the system′s SNR. Therefore the width shall be considered comprehensively to achieve high spectral resolution while meeting the requirement of the SNR index. The design indexes of the ultraviolet double grating spectrometer in this paper: spectral resolution 1 nm wavelength repeatability ±0. 02 nm.

(5)

(5) (4)

。

8 11 13 15 : (1) d; (2)

2δ; (3) Δl; (4)

Δe; (5)

$\Delta l'$; (6) $\Delta \beta$; (7)

ΔX_{j}; (8)

$\Delta x'$。

According to the analysis of the principle of the wavelength scanning mechanism the relation of the wavelength position in the spectrometer with the structure parameter can be determined from formula (5); in addition formula (5) is derived depending on the assumption that formula (4) is workable; i. e. the pendulum rod is vertical to the lead screw at grating zero order. It can be seen from this that the error sources affecting the wavelength repeatability accuracy of the spectrometer include the following [8 11 13 15]: (1) grating constant d; (2) included angle 2δ between incident ray and diffraction ray of grating; (3) pendulum rod length error Δl; (4) runout of the roller on the sliding block Δe; (5) pendulum rod deformation under the action of the spring Δe; (6) waggling error of grating shaft system $\Delta \beta$; (7) zero returning repeatability error of the lead screw mechanism ΔX_{j}; (8) repeatability error of the lead screw mechanism $\Delta x'$.

(1) 、(2) (3)

between positioning magnet steel and Hall sensor is different the positioning accuracy ΔX_c ranges from 3 μm to 5 μm in general. The positioning accuracy of the precise positioning sensor installed on the rotating shaft can be deduced as follows:

$$\Delta_c = \arctan\left(\frac{\Delta X_c}{R}\right) \cdot \frac{p}{360} \qquad (7)$$

R p

° $R = 10$ mm $p = 0.5$ mm。

（7）

0.04 μm。

                                                                                              °

1.8°   3%。

$1.8 \times 0.03/360 \times 0.5$ mm $= 0.075$ μm

°

Where R is the turning radius of magnet steel along the lead screw axis and p is lead screw pitch. For the lead screw mechanism $R = 10$ mm and $p = 0.5$ mm. By substituting system parameters into formula (7) the obtained repeatability accuracy of the precise positioning sensor is about 0.04 μm. The lead screw mechanism is driven by a stepper motor. The step angle error of the stepper motor will have an impact on positioning accuracy. The stepper motor used in this paper is a stepper motor imported from Germany its step angle is 1.8° and its step angle error is better than 3%. Hence limited by the step angle precision of the stepper motor the actual zero returning error of the wavelength scanning mechanism is $1.8 \times 0.03/360 \times 0.55$ mm $= 0.075$ μm. The zero returning accuracy is far too higher than the repeatability accuracy of the lead screw and can be neglected in calculation.

°

1 μm   °

In our spectrometer system error sources （1） （2） and （3） have been determined after selecting gratings; if there is a machining error they will not change with the wavelength scanning process are inherent system errors and affect only the equivalent between wavelength and the step number of the stepper motor $i.\,e.$ wavelength linearity. Wavelength linearity can be calibrated through measurement. The spring tension mode has been improved in this design. Moreover the spring with large rigidity coefficient is used to pre-tighten the roller the sliding block contact surface is finely ground and a high-precision deep groove ball bearing is used as the roller so the radial run-out can be neglected [8 14] . In addition the spring doesn´t tension the pendulum rod integrally so pendulum rod deformation can also be neglected. The grating shaft is supported by a pair of back-to-back mounted high-precision angular contact ball bearings. The measurement of the grating shaft end after precise adjustment shows that the radial run-out is less than 1 μm which can be neglected for this instrument.

ΔX_c 3 ~ 5 μm

                                              :

According to the actual test result rough positioning method is adopted. As the induction distance

（5） x :

The above analysis indicates that the repeatability error of the lead screw mechanism decides

wavelength scanning repeatability accuracy. Accord-
ing to error independence differentiate formula（5）
by the lead screw travel x to obtain：

$$\Delta\lambda = \frac{2d\cos\delta}{ml}\Delta x . \qquad (8)$$

$$\Delta\lambda = \pm 0.002 \text{ nm}$$

$$\Delta x \qquad \pm 5.3 \text{ μm}。$$

$$\pm 2 \text{ μm}$$

$$\pm 1.8 \text{ μm}$$

。

When the wavelength repeatability error is
$\Delta\lambda = \pm 0.02$ nm the repeatability error Δx of the
lead screw shall be better than ± 5.3 μm. The nom-
inal value of the repeatability accuracy of the used
lead screw mechanism is ± 2 μm. The measurement
before assembling indicates that the repeatability ac-
curacy is ± 1.8 μm which meets wavelength re-
peatability requirements.

4

Experimental verification

253、296、313   365 nm   4

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PC

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4 characteristic wavelengths of a mercury lamp
including 253 nm 296 nm 313 nm and 365 nm
have been used to carry out wavelength repeatability
verification of the spectrometer as shown in Fig. 7.
During measurement the mercury lamp is placed
before the entrance slit; the lights emitted by the
mercury lamp enter the spectrometer after passing
through the transmission panel; the PC sends out a
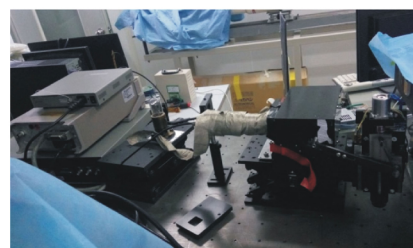
(a) 测量装置
(a) View of measurement equipment
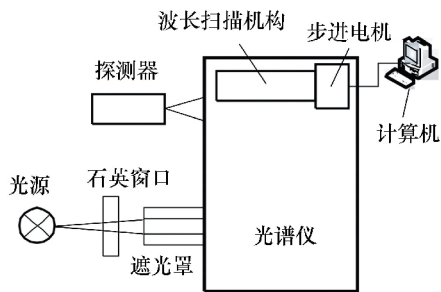
(b) 测量原理图
(b) Measurement schematic diagram

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Fig. 7   Measurement equipment view and its measure-
ment schematic diagram

control command to drive the wavelength scanning
mechanism to return to zero. According to the calcu-
lated whole-process scanning steps scanning is per-
formed from zero to the designated lead screw travel.
The detector acquires the lights out of the exit slit
and the energy distribution at the scanned band can
be obtained. According to theoretical formulas the
step number of the stepper motor is converted into
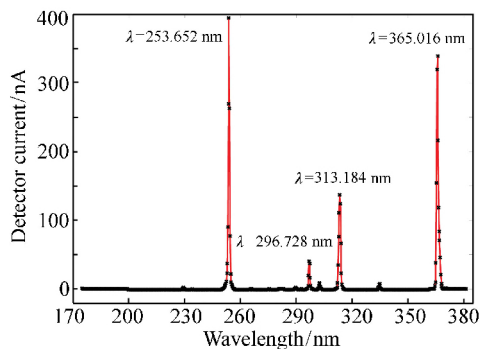the corresponding wavelength number. The measure-

8

Fig. 8   Measurement result within one scanning period

ment result within one scanning period is shown in Fig. 8. The position of the 4 characteristic wavelengths is determined according to the wavelength interval and other non-significant wavelengths are not processed.

5 4

。 5

4

1 。

Scanning is carried out for 5 times. Gaussian fitting of the data at 4 peak valve positions each time of scanning is performed to determine the actual central wavelength and full width at half maximum measured for each characteristic wavelength. The deviation between the central wavelength from 5 times of fitting for the same characteristic wavelength and the average value is taken as the repeatability error of the characteristic wavelength. The statistical results of the repeatability errors of the 4 characteristic wavelengths are shown in Tab. 1.

1 4

Tab. 1 Repeatability error of 4 representative wavelength

/nm	/nm
253. 652	0. 006
296. 728	− 0. 005
313. 184	0. 007
365. 016	0. 004

4

− 0. 005 ~ + 0. 007 nm

0. 8 nm

± 0. 02 nm 1 nm 。

。

According to the measurement result the repeatability errors of the 4 characteristic wavelengths are between − 0. 005 nm and + 0. 007 nm and the

spectral resolution is better than 0. 8 nm which meets the requirements of wavelength repeatability ± 0. 02 nm and spectral resolution 1 nm of ultraviolet double grating spectrometer. This result is consistent with the theoretical analysis result of the wavelength scanning mechanism of the spectrometer indicating that the derived optical-mechanical parameter conversion formulas are correct and that the mechanism design is reasonable. The error analysis is in line with the actual mechanism design.

5

Conclusion

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± 0. 02 nm

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In this paper the wavelength scanning mechanism of the ultraviolet double grating spectrometer has been theoretically calculated according to the concave grating dispersion principle the error sources affecting wavelength repeatability accuracy in the structure design have been analyzed and the repeatability error of the lead screw has been determined to be the main error source. According to the theoretical calculation result a high accuracy lead screw mechanism has been selected the wavelength scanning mechanism has been improved and the design of the whole spectrometer structure has been completed. Using a mercury lamp as the light source the wavelength repeatability accuracy has been verified with 4 characteristic wavelengths of mercury lamp. The experiment result indicates that

the wavelength repeatability meets the requirements of ±0. 02 nm index thereby providing a foundation for subsequent linear calibration of wavelength etc.

The wavelength scanning mechanism design and the error analysis method in this paper have a reference value for the design of like spectrometers.

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