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Measurement of the second-order spectral diffraction efficiency of polarized dual-grating spectrometers

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ABSTRACT

The diffraction efficiency of dual-grating spectrometers is crucial to the research of spectrometer optical systems, meanwhile it is one of the important indexes for evaluating optical system. The second-order spectral diffraction efficiency of the polarized light has not been thoroughly investigated despite its importance to research on dual-grating spectrometers.

However, it affects the imaging quality of the diffractive optical elements, and evaluating of spectrometer optical efficiency. In this work, a test system for the measurement of the second-order spectral diffraction efficiency of polarized light was established. The test system is comprised of a xenon lamp, a collimation system, a polarizer, and a dual-grating spectrometer. The spectral signals of S-and P-polarized light in the band of 285–650 nm were obtained, and the second-order spectral diffraction efficiency measurements of S-and P-polarized light in the band of 285–325 nm were measured. Test results showed that in the 285–325 nm bands, the second-order spectral diffraction efficiency of S-polarized light changed from 30.34% to 4.64%, and that of P-polarized light changed from 3.52% to 0.57%. And the uncertainty of spectrometer system was 2.66%.

1. Introduction

Normally the spectrometers are comprised of polarization-sensitive optics, such as gratings and reflectors. In spectrometers, the grating, as a dispersive optical component, its diffraction efficiency is not only related to the materials, and geometric parameters, but also related to polarization state, wavelength and incident angle of the light. It is very important to evaluate an optical system [1–3], since it determines the spectral energy characteristics and optical efficiency of the spectrometers.

Ke et al. proposed that in the calculation of spectrograph diffraction efficiency, the diffraction efficiency of the whole spectrometer system is a wavelength function [4,5]. Yi et al built a set of experimental equipment for testing the second-order spectral diffraction efficiency of vacuum ultraviolet grating [6]. Their setup functioned on the principle that the spectral reflectance of a sample will be influenced by the second-order diffraction. The absolute measurement of the second-order spectral diffraction efficiency of vacuum ultraviolet grating was obtained. The system uncertainty at 161 nm was 14.08%.Richard et al. proposed the use of a synchrotron light source and an electron beam to excite Ne gas into generating a 46nmsingle-wavelength line radiation [7,8]. The device obtained an accuracy of 6% when used to measure the second-order spectral diffraction efficiency of vacuum ultraviolet grating.

In this work, we performed the test on a dual-grating spectrometer covering a broad ultraviolet-visible band spectral range. The

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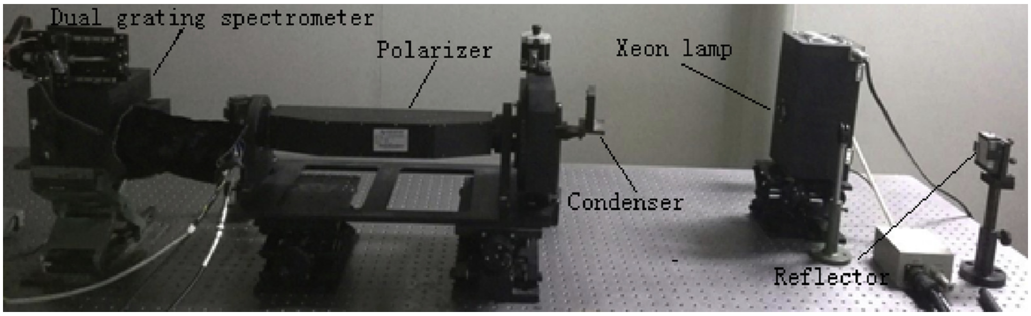

Fig. 1. Device for measuring diffraction efficiency.

first-and second-order spectra of the spectrometer were obtained by using a visible-band high-pass filter. A device for measuring the second-order spectral diffraction efficiency of dual-grating spectrometer in polarized state was constructed by using a xenon lamp, a collimation system and a polarizer S-and P-polarized second-order diffraction efficiencies were calculated in accordance with filter transmittance, first-order diffraction efficiencies and photomultiplier under different polarized state detection signals, and then total uncertainty is obtained. This work is of great significance to the study of the polarization behavior of dual-grating spectrometer under polarized light and improve the optical efficiency [9,10].

2. Measuring system structure and working principle of dual-grating spectrometers

2.1. Measuring system structure of dual-grating spectrometers

Fig. 1 shows the experimental device for the measurement of the second-order spectral diffraction efficiency of dual grating spectrometers in polarized state. The light source is a model L11033 xenon lamp (Hamamatsu Company) with a power of 300 W. The window of the light source is fused silica. The power supply of the light source is the highly stable, DC C8849, and light source has an output light stability of 0.2% and a typical drift value of ± 0.5%/h.

The light emitted by the xenon lamp passes parallelly through an aperture after passing through a condenser. The aperture controls the spot size and is directed toward the polarizer behind the reflector. The system uses a homemade rotating polarizer which is composed of 20 pieces of fused silica plate [11]. The beam has a polarization grade of more than 99%, and a 40 mm diameter.

The polarizer functions on the principle that in accordance with Fresnel's formula, when unpolarized light with a Brewster angle of incidence passes through the fused silica plate surface, the reflected light only has an S component, and the transmitted light is partially polarized with a P component domain. Along with the increase in the number of fused silica plates, the transmission light gradually turns into linear polarized light that is entirely composed of P components.

2.2. Principle and structure of dual-grating spectrometers

The structure of the dual-grating spectrometer is shown in Fig. 2. Its working principle is as follows: S-and P-polarized light is filtered at a vertical incidence into the entrance slit, which is divided by concave grating 1. Then, it passes mirror1, the middle slit, and mirror 2, after being output from the exit slit of concave grating 2. Different wavelengths of monochromatic radiation are generated by concave grating 2 from the exit slit and are finally received by the electrometer mode of the photomultiplier. The photomultiplier type used in this work is R7378 A (Hamamatsu Japan). The optical signal is converted into electronic signals, and an electronics system is used for data acquisition and processing. Two reflectors with a base material that is fused silica with a 5 mm thick plate coated with 160 mm of Al and 100 mm of SiO_2 film are used in the dual-grating spectrometer. Meanwhile two mirrors

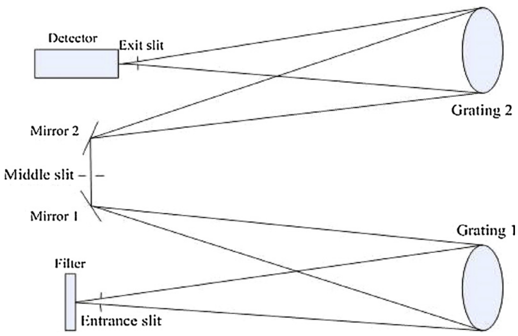

Fig. 2. Structure of dual-grating spectrometer.

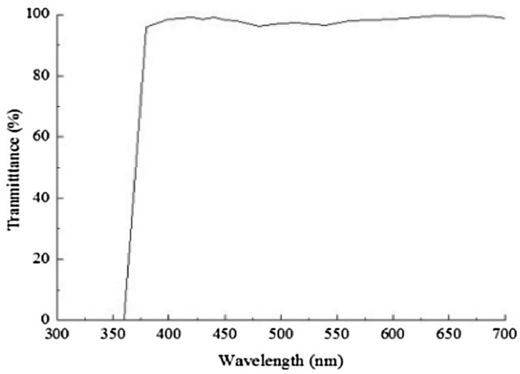

Fig. 3. Curve of filter transmittance.

reflect S-and P-polarized light at an incidence of 61.5°.

Before the test, the spectrometer is calibrated with the characteristic spectral line of a mercury lamp (253.652, 435.834, and 546.074 nm).Then, the wavelength lead screw mechanism was used to scan over the wavelength range of 250–700 nm with an interval of 2 nm.

3. Principle of the measurement of the second-order polarized spectral diffraction efficiency of dual-grating spectrometers

The front filter of the dual-grating spectrometer system employs the high-pass filter of the visible band, and its transmittance curve is shown in Fig. 3. The transmittance of filter is better than 98% in the 380–700 nm bands.

The two concave holographic type gratings were developed by the Changchun Institute of Optics, Fine Mechanics and Physics. The grating has a size of 32 mm × 32 mm, a groove density of 1200 g/mm, and a radius (R) of 100 mm. The curves of the S and P polarization diffraction efficiencies of dual-grating in the 250–700 nm are shown in Fig. 4.

The photomultiplier receives signal $I(\lambda)$. $I(\lambda)$ which is correlated with the light source spectral radiance $L(\lambda)$; the relative aperture square, $(D/f)^2$; total of the incident, middle, and exit slit areas, S; the filter transmittance of spectrometer system τ_{filter}; the energy transfer efficiency, $\tau(\lambda)$; the grating first-order absolute diffraction efficiency, $\varepsilon_1(\lambda)$; the second-order of grating diffraction efficiency, $\varepsilon_2(\lambda)$; the reflectivity of reflectors 1 and 2, $R(\lambda)$; and the detector response, $Res(\lambda)$.

Taking S-polarized light as an example, when a filter is added to the front of the spectrometer system, the photomultiplier detects $I_s(\lambda)$, as shown in Formula (1), where $\varepsilon^2(\lambda)$ is the dual-grating diffraction efficiency, and $R^2(\lambda)$ is the total reflectivity of the two reflectors.

$$L(\lambda_1) \times (D/f)^2 \times S \times \varepsilon_{1s}^2(\lambda_1) \times R_s^2(\lambda_1) \times \tau(\lambda_1) \times \tau_{\text{filter}} \times Res(\lambda_1) = I_s(\lambda) \tag{1}$$

If the spectrometer system lacks a filter, the photomultiplier detects the signal, which will be affected by second-order diffraction efficiency, and the S-polarized light incident to the spectrometer will detect $I_s^{'}(\lambda)$ as expressed by Formula (2).

$$\sum_{n=1}^{2} L(\lambda_n) \times (D/f)^2 \times S \times \varepsilon_{ns}^2(\lambda_n) \times R_s^2(\lambda_n) \times \tau(\lambda_n) \times \text{Res}(\lambda_n) = I_s^{'}(\lambda) \tag{2}$$

Taking the 570–650 nm bands as an example, signal $I_s^{'}(\lambda)$ is the sum of the first-and second-order spectral signals in 285–325 nm. $I_{1s}(\lambda)$ is set as the signal of the photomultiplier in 285–325 nm in absence of a filter, and $I_{1s}(\lambda)$ as expressed by Formula (3).

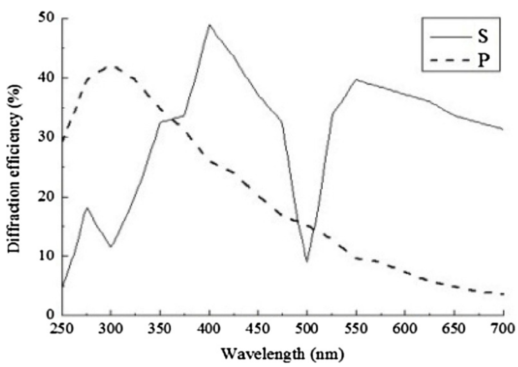

Fig. 4. Curves of the S- and P-polarization diffraction efficiencies of dual-grating.

Table 1
Measurement Data of the Second-Order Spectral Diffraction Efficiency of S-polarized Light.

Wavelength(nm)	I_{1s}(nA)	ε_{1s}^2	ε_{2s}^2	Wavelength(nm)	Δ_s(nA)
285	3.5164	0.1552	0.3034	570	6.8722
295	9.1942	0.1282	0.0979	590	7.0246
305	12.7810	0.1310	0.0742	610	7.2363
315	9.8711	0.1649	0.0861	630	5.1562
325	16.0813	0.2027	0.0464	650	3.6851

$$L(\lambda_2) \times (D/f)^2 \times S \times \varepsilon_{1s}^2(\lambda_2) \times R_s^2(\lambda_2) \times \tau(\lambda_2) \times \mathrm{Res}(\lambda_2) = I_{1s}(\lambda) \tag{3}$$

Then the second-order diffraction efficiency of S-polarized light is obtained by Formulas (1), (2), and (3).

$$\Delta_s(\lambda)/I_{1s}(\lambda) = \varepsilon_{2s}^2(\lambda)/\varepsilon_{1s}^2(\lambda) \tag{4}$$

Here, $\Delta_s(\lambda) = I_s^{'}(\lambda) - I_s(\lambda)/\tau_{filter}$. Similarly, P-polarized light passes the spectrometer, and the second-order diffraction efficiency of the dual-grating spectrometer is derived using Formula (5):

$$\Delta_p(\lambda)/I_{1p}(\lambda) = \varepsilon_{2p}^2(\lambda)/\varepsilon_{1p}^2(\lambda) \tag{5}$$

Here $\varepsilon_{1s}(\lambda)$ and $\varepsilon_{1p}(\lambda)$ are the known first-order diffraction efficiencies of the S- and P- polarizations of the grating.

4. Experimental results

The measurement data of the second-order spectral diffraction efficiency of S- and P-polarized lights and the results of Eqs. (4) and (5) are shown in Tables 1 and 2.

P- and S-polarized lights with and without the filter, respectively, enters the spectrometer. The signal curves received by the photomultiplier are shown in Figs. 5 and 6, which illustrate that the filter only affects the size of the spectrometer signal and does not change the spectral distribution of the light source.

The second-order spectral diffraction efficiency curves of the P- and S-polarized lights are drawn from the test data and calculation results, as shown in Fig. 7.

5. Uncertainty analysis

The sources of measurement uncertainty are as below: (1) stability uncertainty of Xenon lamp in 250–650 nm and 2 h duration. The xenon lamp typical drift value is 0.5%/h, so the stability uncertainty of the xenon lamp is near 1%;(2) Repeatability uncertainty of the spectrometer system is 0.8%;(3) Unpolarization degree uncertainty of the polarizer. In this test, the uncertainty of unpolarization degree is 0.4%; (4) Transmittance uncertainty of the filter, which is 0.5%; (5) Stray light uncertainty, which is 1%. (6) the uncertainty of first-order diffraction efficiency of the grating is 2%.

The uncertainty sources and estimations are shown in Table 3. Since each uncertainty source is unrelated to each other, then the combined standard uncertainty is 2.66%.

6. Conclusion

In this work, a simple test device for measuring the second-order spectral diffraction efficiency of polarized light was established. The second-order spectral diffraction efficiencies of S-and P-polarized lights were measured in accordance with the transmittance of the filter and the known first-order diffraction efficiency of the grating. The test results showed that: (1) In 285–325 nm, the second-order spectral diffraction efficiency of S-polarized light changes from 30.34% to 4.64%, and that of P-polarized light changes from 3.52% to 0.57%; (2)At same wavelengths, the second-order diffraction efficiency of S-polarized light is greater than that of P-polarized light. However, in 285–325 nm, the first-order diffraction efficiency of S-polarized light is smaller than that of P-polarized light; (3)The first-order spectral diffraction efficiency of the dual-grating spectrometer drastically fluctuates, whereas the second-order spectral diffraction efficiency gradually changes; (4)Uncertainty analyzing showed that combined standard uncertainty is

Table 2
Measurement Data of the Second-Order Spectral Diffraction Efficiency of P-polarized Light.

Wavelength(nm)	I_{1p}(nA)	ε_{1p}^2	ε_{2p}^2	Wavelength(nm)	Δ_p(nA)
285	20.7857	0.4070	0.0352	570	1.7998
295	33.1352	0.4173	0.0221	590	1.7534
305	47.8617	0.4171	0.0140	610	1.6069
315	64.9879	0.4070	0.0087	630	1.3887
325	83.9232	0.3964	0.0057	650	1.2142

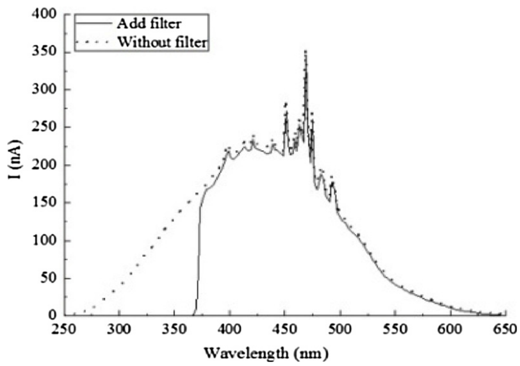

Fig. 5. Curve of the P-polarization signal.

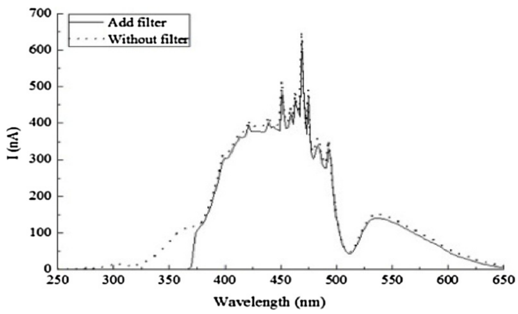

Fig. 6. Curve of the S-polarization signal.

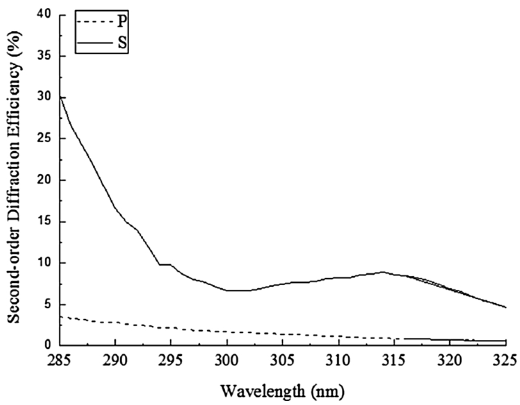

Fig. 7. Curves of the second-order diffraction efficiencies of P- and S-polarizations.

Table 3
Uncertainty Source and Estimations.

Uncertainty source	Uncertainty estimations
Xeon stabilization	1%
Spectrometer system repeatability	0.8%
Unpolarization degree of polarizer	0.4%
Transmittance of filter	0.5%
Stray light	1%
first-order diffraction efficiency	2%
Combined standard uncertainty	2.66%

2.66%. This study provides technical support for research on the related aspects of polarized light dual-grating spectrometers.

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