The second order diffraction efficiency measurements in the vacuum ultraviolet

Yi Qu,[1,*] Shurong Wang[1], Zhenduo Zhang[1,2] and Futian Li[1]

[1]*State Key Laboratory of Applied Optics ,Changchun Institute of Optics, Fine Mechanics and Physics ,Chinese Academy of Sciences, Changchun 130033, China;*
2Graduate School of the Chinese Academy of Sciences, Beijing 100039, China
[*] *quyi972@sohu.com*

Abstract: A simple method for measuring the second order diffraction efficiency in the vacuum ultraviolet (VUV) is described. Spectral reflectance of a mirror will be influenced by the second diffraction order, measured in a spectrophotometer system without filters. The second order diffraction efficiency can be calculated from the different spectral reflectance values. A deuterium lamp and a scintillated photomultiplier are used in the measurement system. The second order diffraction efficiency can be determined from 120nm to 165nm. The result of 0.00579±11.9% is obtained at 161nm.

OCIS codes: (050.0050)Diffraction and gratings; (050.1940)Diffraction; (260.7210)Ultraviolet, vacuum.

References and links

1. Christopher Palmer, *Diffraction Grating Handbook* (Thermo RGL, New York, 2002).
2. A. J. Caruso, G. H .Mount and B. E. Woodgate. “Absolute S- and P-plane polarization efficiencies for high frequency holographic gratings in the VUV,” Appl. Opt. **20**, 1764-1776 (1981).
3. M. V. Vasnetsov, V. Yu. Bazhenov, S. S. Slussarenko, and G.Abbate. “Coupled-wave analysis of second-order Bragg diffraction. I. Reflection-type phase gratings,” J. Opt. Soc. Am. B **26**, 684-690 (2009).
4. F. J. Torcal-Milla, L.M.Sanchez-Brea, E. Bernabeu. “Diffraction of grating with rough edges,” Opt. Express **16**,19757-19769(2008), http://www.opticsinfobase.org/oe/abstract.cfm?URI=oe-16-24-19757.
5. O. P. Brunot, F. Reitic, “Accurate calculation of diffraction grating efficiencies,” SPIE **1919**, 236-247 (1993).
6. I. G. Kuznetsov, E. Wilkinson, D. A. Content, R. A. Boucarut, T. J. Madison. “Grating efficiencies comparison study: calculations versus metrology for various types of high groove density gratings at VUV-UV wavelengths,” Proc. SPIE **5178**, 267-276(2004).
7. W. R. Hunter and D. K. Prinz, “Measuring concave diffraction grating efficiencies at grazing incidence,” Appl.Opt. **16**,3 171-3175 (1977).
8. E. G. Loewen, E.K. Popov and L. V. Tsonev. “Experimental study of local and integral efficiency behavior of a concave holographic diffraction grating,” J. Opt. Soc. Am. A **7**, 1764-1769 (1990).
9. P. Leclere, Y. Renotte and Y. Lion. “Measure of the diffraction efficiency of a holographic grating created by two Gaussian beams,” Appl. Opt. **31**, 4725-4733 (1992).
10. A.McPherson, N. Rouze, W. B. Westerveld, J. S. Risley. “Calibration of a VUV spectrometer-detector system using synchrotron radiation,” Appl. Opt. **25**, 298-310 (1986).
11. R. L. Kendrick, A. McPherson, N. Rouze, W.B. Westerveld, J.S. Risley. “Comparison of methods for determining the second-order detection efficiency of a VUV spectrometer,” Appl. Opt. **26**, 2029-2041 (1987).
12. M. P. Kowalski, J. F. Seely, L. I. Goray, W. R. Hunter, J.C. Rife. “Comparison of the calculated and the measured efficiencies of a normal-incidence grating in the 125–225-A wavelength range,” Appl. Opt. **36**, 8939-8943 (1997).
13. A. R. James, B. S. Samson. *Techniques of Vacuum Ultraviolet Spectroscopy*(Nebraska: Pied Publications,1967).
14. N. Kristianpoller, R. A. Knapp. “Some optical properties of sodium salicylate films,” Appl. Opt. **3**, 915-918 (1964).

#111080 - $15.00 USD Received 11 May 2009; revised 25 Jun 2009; accepted 3 Jul 2009; published 17 Jul 2009

1. Introduction

Efficiency and its variation with wavelength and spectral order are important characteristics of diffraction gratings. Grating efficiency measurements are generally performed with double monochromator systems [1,2]. The first monochromator supplies monochromatic light derived from a continuum source. The grating being tested serves as the dispersing element in the second monochromator. Many new concepts and methods [3-12] for determining grating diffraction efficiency have been put forward. Grating diffraction efficiency measurements are more difficult in the VUV than in other spectral regions. For example, measurements must be performed under vacuum conditions. Vacuum compatible measurements of reflectivity can be complex, and even when commercially available instruments are available, expensive to implement. When a continuum source is used to measure the second order diffraction efficiency, overlapping diffracted orders contribute to the observed signal. This problem is especially serious in the VUV because there are only a few filters that can be used to block multiple-order contributions. In the paper [11], the authors present four different methods for determining the second order absolute diffraction efficiency. Synchrotron radiation, Ne II 46nm line radiation and some special VUV filters are used in their work. A best precision of 6% is obtained.

In this paper, a simple method for measuring the second order diffraction efficiency in the VUV is described. The principle is that spectral reflectance of a mirror will be influenced by the second diffraction order, measured in a spectrophotometer system without filters. The second order diffraction efficiency can be calculated from the different spectral reflectance values.

2. Setup and Methods

The structure of the systems used to measure second order diffraction efficiency in the VUV is shown in Fig.1. The whole system works under vacuum conditions because VUV radiation cannot propagate in atmosphere.

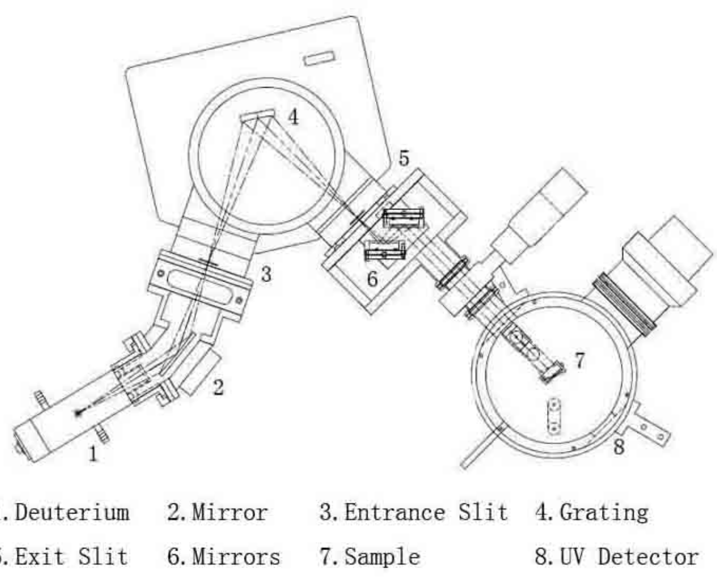

Fig.1. Schematic diagram of the second order diffraction efficiency measurement system

The light source is a 30*W* deuterium lamp (1) with a Magnesium Fluoride (MgF_2) window permitting an operational range of 120nm to 380nm. Spectral radiance of the deuterium lamp is known. The mirror (2) is a light source condenser. It uses a first surface optical design to focus the source energy to the entrance slit (3) of a scanning monochromator to illuminate the grating (4). The scanning monochromator (McPherson 234/302) focal length is 200mm. The aperture ratio is f/4.5. The resolution is 0.1nm with 0.01mm slit width. The grating is a concave holographic grating (1200G/mm). It is also the grating being tested. The energy leaving exit slit (5) is collimated using two cylinder mirrors (6) and delivered a spot at the sample (7) and the detector (8). The detector is a R6095 photomultiplier mounted close to a sodium salicylate scintillator film.

Spectral reflectance measurement is as follows. Detect the signal $I_0(\lambda)$ when no mirror is in the light path. The signal $I_0(\lambda)$ is correlated with the light source spectral radiance $L(\lambda)$, power of system aperture ratio $(D/f)^2$, area S, energy transfer efficiency $\tau(\lambda)$, the first order absolute diffraction efficiency $\mathrm{Eff}_1(\lambda)$, detector response Res(λ) at wavelength λ and bandwidth $d\lambda$.

$$I_0(\lambda) = \mathrm{L}(\lambda) \times (\frac{D}{f})^2 \times S \times \tau(\lambda) \times \mathrm{Eff}_1(\lambda) \times \mathrm{Res}(\lambda) \times \mathrm{d}\lambda \tag{1}$$

Put the mirror into the light path. The signal $I_R(\lambda)$ is obtained.

$$I_R(\lambda) = \mathrm{L}(\lambda) \times (\frac{D}{f})^2 \times S \times \tau(\lambda) \times \mathrm{Eff}_1(\lambda) \times \mathrm{Res}(\lambda) \times \mathrm{R}(\lambda) \times \mathrm{d}\lambda \tag{2}$$

Spectral reflectance $R(\lambda)$ of the mirror is

$$R(\lambda) = \frac{I_R(\lambda)}{I_0(\lambda)} \tag{3}$$

$I_0(\lambda_1)$ and $I_R(\lambda_1)$ at wavelength λ_1 will be influenced by the second diffraction order $\mathrm{Eff}_2(\lambda_2)$ at wavelength λ_2 if no cut-off filter is used in the measurement system. Here $\lambda_1 = 2\lambda_2$ and $d\lambda_1 = 2d\lambda_2$.

$$I_0(\lambda_1) = \sum_{n=1}^{2} \mathrm{L}(\lambda_n) \times (\frac{D}{f})^2 \times S \times \tau(\lambda_n) \times \mathrm{Eff_n}(\lambda_n) \times \mathrm{Res}(\lambda_n) \times \mathrm{d}\lambda_\mathrm{n} \tag{4}$$

$$I_R(\lambda_1) = \sum_{n=1}^{2} \mathrm{L}(\lambda_n) \times (\frac{D}{f})^2 \times S \times \tau(\lambda_n) \times \mathrm{Eff_n}(\lambda_n) \times \mathrm{Res}(\lambda_n) \times R(\lambda_n) \times \mathrm{d}\lambda_\mathrm{n} \tag{5}$$

The spectral reflectance $R^{'}(\lambda_1)$ influenced by the second diffraction order is

$$R^{'}(\lambda_1) = \frac{I_R(\lambda_1)}{I_0(\lambda_1)} = \frac{\sum_{n=1}^{2} \mathrm{L}(\lambda_n) \times \tau(\lambda_n) \times \mathrm{Eff_n}(\lambda_n) \times \mathrm{Res}(\lambda_n) \times \mathrm{d}\lambda_\mathrm{n}}{\sum_{n=1}^{2} \mathrm{L}(\lambda_n) \times \tau(\lambda_n) \times \mathrm{Eff_n}(\lambda_n) \times \mathrm{Res}(\lambda_n) \times R(\lambda_n) \times \mathrm{d}\lambda_\mathrm{n}} \tag{6}$$

The ratio of $\mathrm{Eff}_2(\lambda_2)$ to $\mathrm{Eff}_1(\lambda_1)$ is

$$\beta = \frac{\mathrm{Eff}_2(\lambda_2)}{\mathrm{Eff}_1(\lambda_1)} = \frac{L(\lambda_1) \times \tau(\lambda_1) \times \mathrm{Re}\,s(\lambda_1) \times d\lambda_1}{L(\lambda_2) \times \tau(\lambda_2) \times \mathrm{Re}\,s(\lambda_2) \times d\lambda_2} \times \frac{R(\lambda_1) - R^{'}(\lambda_1)}{R^{'}(\lambda_1) - R(\lambda_2)} \tag{7}$$

The detector is a conventional photomultiplier mounted close to a sodium salicylate scintillator film. The quantum efficiency of sodium salicylate is approximately equal between 120nm and 330nm [13,14]. Detector response is constant at the scintillator emission

#111080 - $15.00 USD Received 11 May 2009; revised 25 Jun 2009; accepted 3 Jul 2009; published 17 Jul 2009

wavelength throughout this range. The deuterium lamp spectral radiance, energy transfer efficiency and the first order absolute diffraction efficiency are known in formula (7). The second order absolute diffraction efficiency can be calculated with $R(\lambda_1)$, $R(\lambda_2)$ and $R'(\lambda_1)$. The deuterium lamp spectral radiance curve is shown in Fig.2. The data is from representative calibration curves measured by the standard organization Physikalisch-Technische Bundesanstalt (PTB).

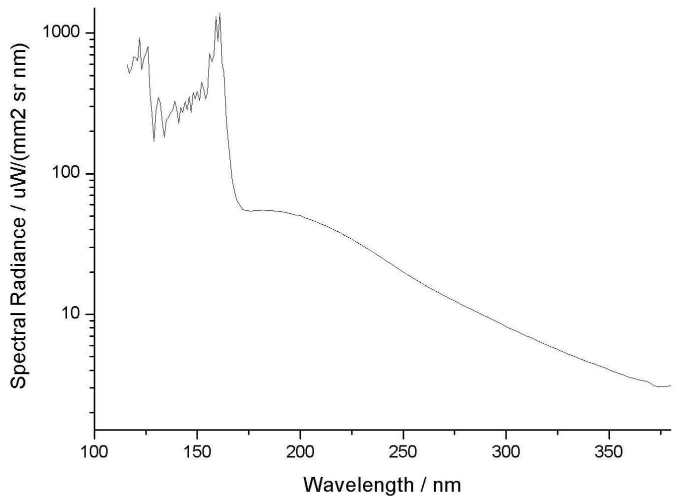

Fig. 2. Deuterium lamp spectral radiance curve

3. Results

The true spectral reflectance curve $R(\lambda)$ and spectral reflectance curve $R'(\lambda)$ influenced by the second diffraction order are shown in Fig.3.

An obvious deviation can be found between $R(\lambda)$ and $R'(\lambda)$. Since the cut-off wavelength of MgF_2 is about 115nm. The second diffraction order will influence the spectral reflectance at 230nm and longer wavelength. The third diffraction order will influence the spectral reflectance between 345nm and longer. Take $\lambda_1 = 322nm$ for instance, the parameters of the measurement system are list in table1.

Table 1. Parameters of the measurement system

Wavelength nm	Deuterium lamp spectral radiance $\mu W/(mm^2 \cdot sr \cdot nm)$	Energy transfer efficiency	The first order absolute diffraction efficiency
322	5.786	0.636	0.33
161	1373	0.422	-

#111080 - $15.00 USD Received 11 May 2009; revised 25 Jun 2009; accepted 3 Jul 2009; published 17 Jul 2009

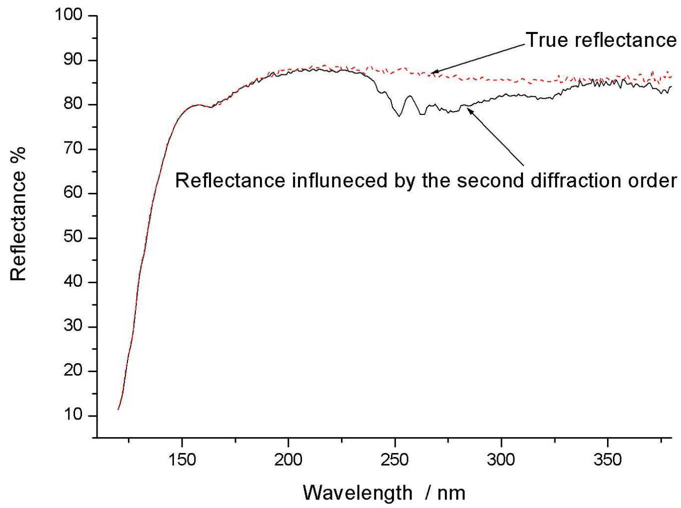

Fig.3 True spectral reflectance and spectral reflectance influenced by the second diffraction order

Five mirror samples with different spectral reflectance are measured. The second order absolute diffraction efficiency is calculated with R(161),R(322)and R'(322). The results are shown in table2.

Table 2. Results of the second order absolute diffraction efficiency

	R(161)	R(322)	R'(322)	The second order absolute diffraction efficiency (%)
Sample 1	0.801	0.851	0.814	0.543
Sample 2	0.59	0.862	0.657	0.583
Sample 3	0.729	0.854	0.758	0.631
Sample 4	0.781	0.834	0.796	0.483
Sample 5	0.59	0.856	0.65	0.654
Average	-	-	-	0.579
STD	-	-	-	0.0689
Relative STD	-	-	-	11.9

4. Discussion and conclusion

A simple method for measuring the second order diffraction efficiency in the VUV is described. The result of 0.00579±11.9% is obtained at 161nm second order, 322nm wavelength. The main measurement error comes from the deuterium lamp. The uncertainty of deuterium lamp spectral radiance is 14% in the VUV. Further, deuterium lamp degradation due to polymerization of residual vacuum contaminants on the MgF_2 window is difficult to quantify and may add errors in the results. A better result can be obtained if a reference light path is added to the measurement system.

#111080 - $15.00 USD Received 11 May 2009; revised 25 Jun 2009; accepted 3 Jul 2009; published 17 Jul 2009

Acknowledgments

This work is supported by the National Natural Science Foundation (40675083) and State Key Laboratory of Applied Optics of the Chinese Academy of Science. The authors would like to thank Erik Schoeffel from McPherson, Inc.

#111080 - $15.00 USD Received 11 May 2009; revised 25 Jun 2009; accepted 3 Jul 2009; published 17 Jul 2009