Study of transmission grating diffraction efficiencies for soft X-ray

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Abstract Tansmission grating spectrometers are extensively used to measure absolute X-ray spectra in a photon-energy range below 1000 eV. The transmission grating, as its dispersive element, must be calibrated to obtain its diffraction efficiencies. Calibrations of absolute diffraction efficiencies of the transmission grating at photon energy of 844 eV have been carried out on Beijing Synchrotron Radiation Facility. With the aid of grating model, all of the grating structure parameters have been determined and the absolute diffraction efficiencies in a photon-energy range below 2000 eV have also been calculated and discussed.

Keywords Synchrotron radiation, Transmission grating, Diffraction efficiency

1 Introduction

Laser-produced plasmas convert a large fraction of the incident laser energy into X-ray radiation in a photon-energy range below 1000eV. So quantitative measurements of the soft X-ray spectra from the laser-irradiated targets are very important in the investigations on the energy transport, the energy balance in the plasmas, the atomic physical processes in the high-energy density material and so on. Previously, the X-ray radiation was measured by a multichannel X-ray analyzer, in which X-ray diodes are combined with various thin foil filters, but this method has a disadvantage of poor spectral resolution. Much better spectral resolution has been achieved by using the transmission grating spectrometer.[1] However, quantitative measurements of X-ray spectra require calibrations of transmission grating diffraction efficiencies.

Schnopper *et al*[2] and Brauninger *et al*[3] calibrated the transmission grating efficiencies for soft X-ray, respectively. In their calibration experiments, the dominant monoenergetic X-ray radiation from the X-ray source is mixed with stray X-ray radiation. The experimental results are affected by the stray X-ray radiation due to their contribution to the zero order of the grating under test.

In this paper, we present another method that is used to calibrate the transmission grating efficiencies for soft X-ray on Beijing Synchrotron Radiation Facility. At first, synchrotron radiation was monochromatized by the combination of a multilayer mirror with a proper thin-foil filter, and a clean monoenergetic X-ray beam was obtained as an X-ray source. Then, relative diffraction efficiencies of the test grating at photon energy of 844eV were measured, in which diffraction image of the test grating was recorded with a soft X-ray film 5FW. At the same time, the relative response curve of the soft X-ray Film

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5 FW to 844 eV X-ray was calibrated. After that, total diffraction efficiencies at three different photon energies were experimentally obtained. Finally, with the aid of grating model, all of the test grating parameters were obtained, and the diffraction efficiencies of the test grating in a photon-energy range below 2000 eV were also calculated and discussed. This paper is preseted as follows. In section 2.1, we describe the calibration experiments for relative diffraction efficiencies of transmission grating. The experimental response results for the soft X-ray Film 5 FW to 844 eV X-ray are also presented and compared with the theoretical curve. section 2.2 is devoted to the total diffraction efficiency measurements of the test grating and the absolute diffraction efficiencies for 844 eV X-ray are given. In section 2.3, we present the grating model and the determined structure parameters of the test grating. The theoretical one-side mth order diffraction efficiencies of the grating in a photon-energy range below 2000eV are also given. In section 2.4, discussion and conclusion are made.

2 Measurement method

2.1 Relative diffraction efficiency calibrations and rsults

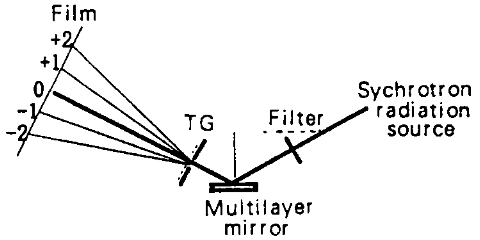

Fig.1 Experimental arrangement for calibration of the TG relative diffraction efficiencies

Fig.1 is a schematic diagram of the experimental arrangement for relative diffraction efficiency calibration. Synchrotron radiation, which transmit through the thin-foil filter, illuminates the multilayer mirror with a grazing incident angle θ. By selection of the filter material and the grazing incident angle θ, the clean monoenergetic X-ray radiation with a wavelength of λ was obtained as an X-ray source in the reflection direction of the multilayer mirror. In terms of Bragg's formula, the following expression is given,

$$\lambda = 2d\sin\theta \qquad (1)$$

where $2d$=7.6 nm is the periodical constant of the multilayer. The tested transmission grating is a substrate-free one with coarse support structure, as shown in Fig.2. The nominal grating space is about 1.0μm. The tested grating with a 100μm wide slit was put in at the reflection direction of the multilayer mirror, and a diffraction image of the tested grating was produced in the far-field plane and recorded by using the soft X-ray film 5 FW, which was mounted in a camera with exposure-time control. The distance between the tested grating and the recording X-ray film is about 156 mm.

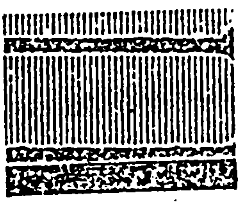

Fig.2 An electron micrograph of a small portion of the tested grating

The typical optical density scan of the film recording is shown in Fig.3. In order to transfer the optical density into X-ray intensity, the response curve of the recording film to the soft X-ray has also been measured. The measured results were compared with the theoretical curve, as shown in Fig.4. By resorting to the response curve of the recording film, the optical density of diffraction order of the tested grating, as shown in Fig.3, were converted into X-ray exposure. Then, the measured relative one-side mth order diffraction efficiencies were obtained from the ratio of two peak X-ray exposures. The experimental results for the two shots are given in Table 1. The grating space was also given in Table 1, which was deduced from the measured distance between two peaks of diffraction orders.

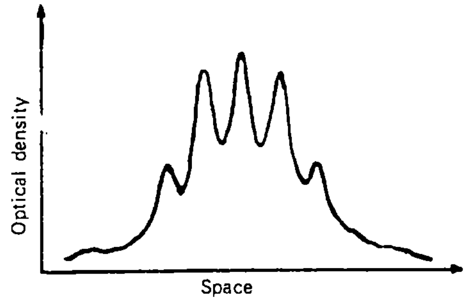

Fig.3 Typical optical density scan of the film recording for the TG diffraction efficiency calibration

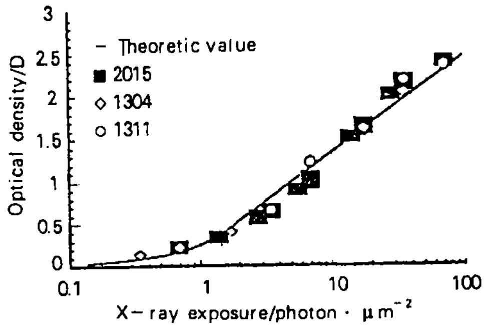

Fig.4 Comparison of the experimental response results for film 5 FW to X-ray at photon energy of 844 eV with theoretical curve

Table 1 Measured grating space and relative one-side mth order efficiencies for 844 eV X-ray

Shot No.	$\eta^{(1)}/\eta^{(0)}$	$\eta^{(2)}/\eta^{(1)}$	grating spacing/μm
1	0.762	0.221	0.909
2	0.781	0.312	0.918

2.2 Total diffraction efficiency measurements

The experimental arrangement is shown in Fig.5. A slit and the tested transmission grating with the same size slit were mounted on different holes of the rotor. By revolving the rotor, the slit and the tested grating were exactly located at the reflection direction of the multilayer mirror, alternatively. The X-ray flux transmitted through the slit and the total diffraction X-ray flux of the tested grating were measured by a silicon diode detector AXUV-100, respectively. Total diffraction efficiency of the tested grating was obtained from the ratio of measured diffraction X-ray flux of the tested grating to X-ray flux from the slit. The distance between the rotor and the detector is about 40 mm. The sensitive area of the detector is about 10×10mm^2 and large enough to receive all diffraction X-ray flux of the tested grating. The dark current of the detector is about 1 pA, while the signal current above 150 pA. We measured total diffraction efficiencies of the tested grating at three different photon energies, respectively. The measurements were carried out several times at each photon energy. The measured average values and experimental errors at the three photon energies are listed in Table 2.

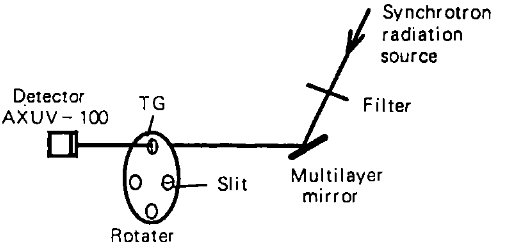

Fig.5 Experimental arrangement for total diffraction efficiency measurements

Total diffraction efficiency of the tested grating can be expressed as

$$T = \eta^{(0)} + 2\eta^{(1)} + 2\eta^{(2)} + \cdots + 2\eta^{(n)} \qquad n \geq 1 \tag{2}$$

where $\eta^{(0)}$, $\eta^{(1)}$, $\eta^{(2)}$, $\cdots$, and $\eta^{(n)}$ represent the absolute one-side nth order diffraction efficiencies, respectively.

Table 2 Measured total diffraction efficiencies at three photon energies

Photon energy/eV	270	660	844
T	0.204±0.022	0.223±0.007	0.248±0.010

Table 3 Measured absolute one-side mth order efficiencies at photon energy of 844 eV

Shot NO.	$\eta^{(0)}$	$\eta^{(1)}$	$\eta^{(2)}$
1	0.0905	0.0690	0.0152
2	0.0813	0.0635	0.0198

As shown in Fig.3, the absolute one-side efficiencies above the second order for the tested grating are very low and can be neglected. By substituting the measured relative one-side diffraction efficiencies at photon energy of 844 eV (given in Table 2) into equation (2) the measured absolute one-side diffraction efficiencies at photon energy of 844 eV can be obtained, as shown in Table 3.

2.3 Grating model and the determined grating parameters

We adopt the same grating model as that of Schnopper *et al.*[2] This grating model assumes that the grating wires have a rectangular cross section and takes into account the transmission and phase shift of waves which penetrate the grating wire. One-side mth diffraction efficiency of transmission grating for $m \neq 0$ is expressed as

$$\eta^{(m)} = \frac{n^{(m)}(q)}{n_0(q)} = (1-f)\Big[\frac{\sin(Mm\pi)}{M\sin(m\pi)}\Big]^2\Big\{\frac{\sin(\frac{a}{d})m\pi}{(m\pi)}\Big\}^2$$
$$\times[1+\exp(-2qZk) - 2\exp(-qZk) - 2\exp(-qZk)\cos(qZ\delta)] \tag{3}$$

For m=0, the expression becomes

$$\eta^{(0)} = \frac{n^{(0)}(q)}{n_0(q)} = (1-f)\{(\frac{a}{d})^2 + (1-\frac{a}{d})^2\exp(-2qZk) + 2(\frac{a}{d})(1-\frac{a}{d})\exp(-qZk)\cos(qZ\delta)\} \tag{4}$$

where f is the fraction of the grating obscured by supporting structure; $n_0(q)$ is the radiative flux illuminating the grating with a slit; M is the number of wires in the illuminated part of the grating; d is the grating spacing; a is the width of the grating opening; Z is the thickness of the grating wire; k is the imaginary part of the refractive index. and $n = 1 - \delta$ is the real part of the refractive index. The ratio $\eta^{(m)}/\eta^{(1)}$ for $m > 1$ can be obtained from Eq.(3) and is given by

$$\frac{\eta^{(m)}}{\eta^{(1)}} = \Big[\frac{\sin(a/d)m\pi}{m\sin(a/d)\pi}\Big] \tag{5}$$

For m=0, the ratio $\eta^{(1)}/\eta^{(0)}$ can also be deduced from Eq.(3) and Eq.(4), and is expressed as

$$\frac{\eta^{(1)}}{\eta^{(0)}} = \Big[\frac{\sin(\frac{a}{d}\pi)}{\pi}\Big]^2\frac{[1+\exp(-2qZk) - 2\exp(-qZk)\cos(qZ\delta)]}{[(\frac{a}{d})^2 + (1-\frac{a}{d})^2\exp(-2qZk) + 2(\frac{a}{d})(1-\frac{a}{d})\exp(-qZk)\cos(qZ\delta)]} \tag{6}$$

As seen from Eq.(5), the ratio $\eta^{(m)}/\eta^{(1)}$ is a function of the radio (a/d) only. By substituting the measured relative diffraction efficiencies of the tested grating for 844 eV X-ray (listed in Table 1) into Eq.(5), a/d=0.325 is obtained by a least square analysis. The determined a/d value and the ratio $\eta^{(1)}/\eta^{(0)}$ (listed in Table 1) substituted into Eq.(6), the thickness of the grating wire is determined to be 0.163μm. Using the structure parameters a/d and Z determined, the parameter f=0.323 was extracted from the measured total diffraction efficiencies at photon energy of 844eV and Eq.(2)~(4)

By using all structure parameters of the tested grating known, absolute one-side mth order diffraction efficiencies were calculated and the curves are shown in Fig.6. The experimental results at photon energy of 844 eV are also illustrated in Fig.6.

2.4 Discussion and conclusion

As we know, the grating wire cross section is not exactly rectangular, so the determined structure parameters from the measured absolute diffraction efficiencies at photon energy of 844 eV are approximate values. By using these parameters the total diffraction efficiencies of the tested grating in a photon-energy range below 1000 eV were calculated and compared with the measured results, as shown in Fig.7. The measured results at different photon energies are all consistent with the calculated curve within the experimental errors, which implies that the approximate parameter values for the tested grating at other photon energies are the same as those determined at photon energy of 844 eV. So it is acceptable to assume that the wire of the tested grating has a rectangular cross section and the calculated one-side mth order diffraction efficiencies, as shown in Fig.6, are believable.

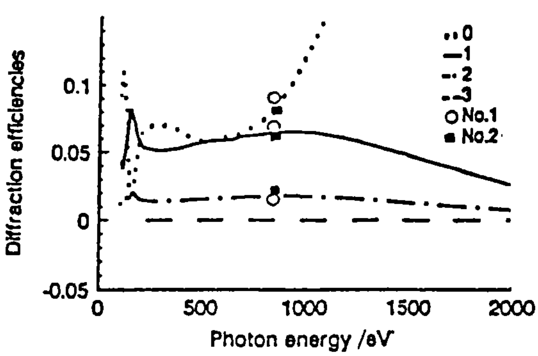

Fig.6 Calculated absolute one-side mth order diffraction efficiency curve

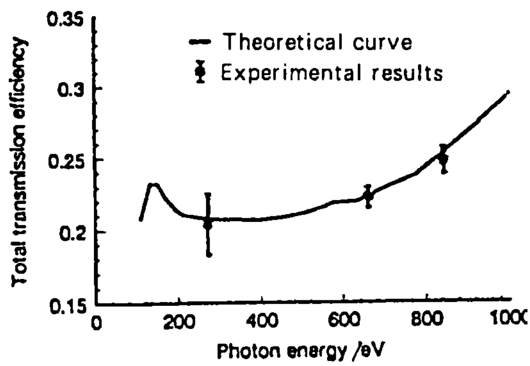

Fig.7 Comparison of measured total diffraction efficiencies with predicted ones

In the experiments we calibrated the absolute diffraction efficiencies only at photon energy of 844 eV. The calibration experiments at more photon energies, especially at higher photon energy have been planned and are in progress.

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