Chapter 58
Broadband High-Resolution Imaging Spectrometers for the Soft X-Ray Range

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Abstract We develop imaging (stigmatic) XUV spectrometers with the use of plane grazing-incidence varied line-space (VLS) diffraction gratings and focusing normal-incidence multilayer mirrors (MMs), including broadband aperiodic ones. A stigmatic 12–30 nm spectrometer with a resolving power of at least 500 is demonstrated.

58.1 Introduction

Grazing-incidence spectrometers with classical concave gratings for a wavelength range $\lambda \sim 20$–300 Å are astigmatic. This entails a drastic lowering in the irradiance of spectral lines and the loss of spatial resolution. Using focusing normal-incidence MMs in combination with varied line-space (VLS) diffraction gratings (DGs) makes it possible to remedy these defects.

Cornu [1] realized that monotonic variations in line spacing modified the curvature of the diffracted wavefronts and the spectral (horizontal) focal curve. Hettrick and Bowyer [2] proposed a way to obtain a stigmatic spectral image in the XUV by sending a converging homocentric beam onto a VLS DG whose local line

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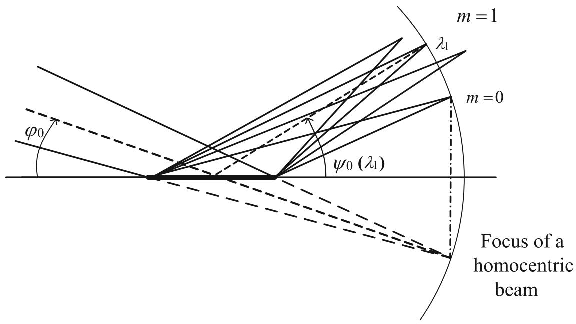

Fig. 58.1 Cancellation of astigmatism at one wavelength (λ_1) in the incidence of a converging beam on a plane VLS grating (φ_0 and ψ_0 are the grazing angles of the central rays of the incident and diffracted beams, and m is the order of diffraction)

density has to obey the local grating equation to bring the diffracted rays in the principal plane to a common focus. However, in this case, the spectral image is stigmatic at only one wavelength (Fig. 58.1).

The line density $p(w)$ of a VLS grating is conveniently expressed as

$$p(w) = p_0 + p_1 w + p_2 w^2 + p_3 w^3 + \cdots. \tag{58.1}$$

Factor p_1 modifies the spectral curve and p_2 and p_3 remove meridional coma and spherical aberration. In the approach of [2], p_0 and φ_0 are free parameters.

58.2 Spectrometer Design

Let a slightly astigmatic beam be incident on a plane VLS grating (Fig. 58.2). Let L_1 be the distance of the vertical focus of the incident beam from the grating center and L_2 be that of the horizontal one ($L_1 > L_2$). Then, it is possible to cancel astigmatism at two wavelengths, λ_1 and λ_2, at a sacrifice of one free parameter (either p_0 or φ_0). The slightly astigmatic beam incident on the grating is produced by a near normal-incidence MM, which images a point source. The sequence of steps is as follows: we define the spectral range, and then determine λ_1 and λ_2 to minimize the defocusing in the range. If we define φ_0, then $p_0 = \sqrt{(L_1/L_2 - 1)(\sin^2\varphi_0)/\lambda_1\lambda_2}$. If, alternatively, we define p_0, then $\varphi_0 = \arcsin\left(mp_0\sqrt{\lambda_1\lambda_2}/\sqrt{L_1/L_2 - 1}\right)$. The grating parameters p_i result from (58.2) after Taylor series decomposition:

$$\begin{aligned} mp(w)\lambda_{1,2} = \cos\left[\operatorname{arcctg}\left(\operatorname{ctg}\varphi_0 - \frac{w}{L_2\sin\varphi_0}\right)\right] - \\ - \cos\left[\operatorname{arcctg}\left(\operatorname{ctg}\psi_0^{1,2} - \frac{w}{L_1\sin\psi_0^{1,2}}\right)\right]. \end{aligned} \tag{58.2}$$

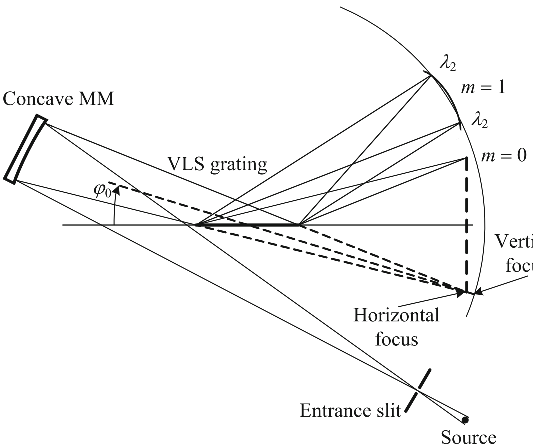

Fig. 58.2 Cancellation of astigmatism simultaneously at two wavelengths, λ_1 and λ_2

We calculated several 1-m-long spectrometer versions for the 120–300 Å range, with $\lambda_1 = 144$ Å, $\lambda_2 = 270$ Å, and $p_0 = 600$ mm^{-1}. For a grating area of 50 × 20 mm, the ray trace images of a point source are all confined to one detector pixel. The plate scales are about 5 Å/mm and, in view of the detector pixel size of 13 μm, typical practical resolution is expected at ~(0.05–0.07) Å throughout the range. The spectrometer may be equipped with a narrowband periodic multilayer mirror or a broadband aperiodic one. In the latter case, the operating range may span an octave in wavelength or more. In the instrument described below, the MM was mounted at an angle of incidence of 7.59° and the VLS grating was mounted at a grazing angle of 6.44°.

58.3 Spectrometer Implementation

The spectrometer layout is shown in Fig. 58.3. The XUV source was the plasma of a plane LiF target irradiated by a 1.06 μm, 0.5 J, 10 ns laser pulse. For a test, we took an aperiodic MM spanning a range of at least 125–250 Å [3].

The VLS grating ($p_0 = 600$ mm^{-1}, $p_1 = 2.32$ mm^{-2}) was fabricated by e-beam lithography (EBL) followed by inductively coupled plasma (ICP) etching. A 100 nm tungsten film was deposited on a glass substrate, which was next spin-coated with the positive-tone e-beam resist PMMA A4 (Microchem, 5000 rpm, 90 s). It was then exposed to EBL (beam energy 50 keV, current 15.5 nA, write field 600 × 600 μm, dwell time 0.14 ms). The resist was developed in MIBK:IPA (1:3) for 120 s and IPA for 60 s. Finally, the structure was formed with SF_6 ICP etching followed by O_2 plasma cleaning.

Due to its high light-gathering power, the spectrometer records the spectrum in one 0.5 J laser shot. The portion shown in Fig. 58.4 contains the lines of Li III and F V–F VII. The closest first-order lines resolved with a safety margin are the

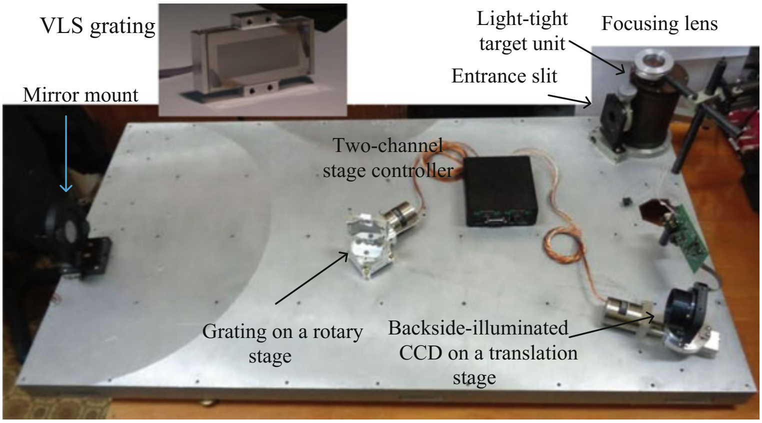

Fig. 58.3 Spectrometer elements accommodated on a 1.1-m-long base plate. VLS grating (top of drawing: tungsten VLS grating made by e-beam lithography)

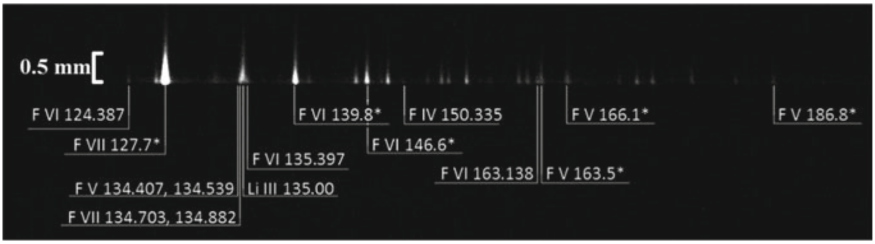

Fig. 58.4 Single-shot first-order stigmatic spectrum of an LiF target excited by a 0.5 J pulse. Asterisks indicate unresolved line arrays. Entrance slit width: 30 μm

163.138 Å line of F VI and the {163.456, 0.501, 0.558, 0.596 Å} unresolved line array of F V, yielding a conservative figure $\lambda/\delta\lambda \sim 510$. The line half-widths typically correspond to four detector pixels (52 μm). In view of the plate scale (5.5 Å/mm at 125 Å, 6.3 Å/mm at 200 Å), this corresponds to $\lambda/\delta\lambda \sim 450$ and 600, respectively. The strongest line arises from the 3d → 2p (127.653 Å, 127.796 Å) transitions in F VII, which saturates the CCD detector pixels corresponding to the near-surface portion of the space-resolved spectral image and broadens the apparent linewidth. Its second order is much weaker and is safely resolved, testifying to a resolving power of ~900.

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