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Recent advances in etched multilayer X-ray optics

J. M. André (1), A. Sammar (1), S. Bac (1, 2), M. Ouahabi (1), M. Idir (1, 2), G. Soulié (1, 2) and R. Barchewitz (1, 2)

(1) Laboratoire de Chimie Physique (LCP), Université Paris 6, U.A. CNRS 176, 11 rue Pierre et Marie Curie, 75231 Paris Cedex 05, France
(2) Laboratoire pour l’Utilisation du Rayonnement Electromagnétique (LURE), Université Paris 11, 91405 Orsay Cedex, France

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Résumé. — Nous présentons les récents progrès réalisés au Laboratoire de Chimie Physique de l’Université Paris 6 dans le domaine de l’optique X utilisant des multicouches gravées. Nous donnons des résultats concernant les réseaux d’amplitude multicouches, les monochromateurs multicouches à haute résolution, les polychromateurs X et les lentilles linéaires multicouches dites de Bragg-Fresnel.

Abstract. — We present the recent advances achieved in the Laboratoire de Chimie Physique of Université Paris 6, in the field of the soft X-ray etched multilayer optics. Modellings and characterizations are given for the laminar multilayer amplitude gratings, the highly resolutive X-ray multilayer monochromators, the X-ray polychromators and the Bragg-Fresnel multilayer linear lenses.

Introduction.

By combining the thin film deposition techniques with the technology of microstructure manufacturing, it is now possible to make new X-ray optical devices based on etched multilayer structures. Since the beginning of the eighties, the LCP deals with the modelling and the characterizations of the performances of these devices in the soft X-ray range. We present the principle of several devices based on laminar multilayer gratings and Bragg-Fresnel optics, and recent results concerning their characterizations.

1. Laminar multilayer amplitude grating (LMAG).

The LMAG is a grating obtained by etching a multilayer interferential mirror (MIM) down to the substrate, according to a periodic rectangular profile [1] (See Fig. 1.) The system is doubly periodic (in-depth with period d and laterally with period D). Thus a LMAG diffracts in an
1660 JOURNAL DE PHYSIQUE III N° 9

optimal manner a wavelength $\lambda$ at a multilayer diffraction order $m$ and at a grating diffraction order $p$, on condition that the glancing angle $\theta_0$ satisfies the following relationship [2]

$$m\lambda = d \sin \theta_0 \left[ 1 + \sqrt{1 - 2 \frac{\cos \theta_0 p\lambda}{\sin^2 \theta_0 D} - \frac{1}{\sin^2 \theta_0} \left( \frac{p\lambda}{D} \right)^2} \right].$$  \hspace{1cm} (1)

It results that the optimal angle $\theta_0$ to diffract at the order $p$, depends on $p$. Different dynamical theories have been developed to calculate the diffraction patterns and the efficiencies of the LMAGs: differential theory [3, 4] and partial summation method [5]. Figure 2 shows in comparison the observed and computed diffraction patterns at $\lambda = 1.33$ nm for $p = -1$ (2a), $p = 0$ (2b), $p = +1$ (2c) with a LMAG with the following features

MIM : 80 Mo/C bilayers, $d = 4.4$ nm, $\gamma = d_{Mo}/d = 4/7$;

grating : $D = 1 \, \mu m$, $\Gamma = 0.5$.

2. Highly resolutive X-ray multilayer monochromator (HRXMM).

The purpose of this device is to achieve a Bragg monochromator with both a narrow bandwidth given by Sammar et al. [6]. The fundamental idea is to diminish both the average absorption reflectivity (similar to the reflectivity of MIMs). The principle of such a device was recently given by Sammar et al. [6]. The fundamental idea is to diminish sboth the average absorption coefficient of the diffractive medium and the reflection factor at each interface in order to decrease the bandwidth. To keep a high peak reflectivity while getting a narrow bandwidth, it is necessary that a sufficiently large number of multilayer periods $N$ contributes to the
constructive interferences involved in the Bragg diffraction. In practice, one has to make a LMA with narrow multilayer bars (i.e. small $f$) and a large number of periods $N$. The value of $f$ and $N$ needed to reach a specified theoretical performance, can be deduced from dynamical calculations [3].

Figure 3 shows the Al Kα and W Mα, β spectra obtained by means of a HRXMM and of the corresponding MIM. The characteristics of the structures are: MIM : 150 W/Si bilayers,
Fig. 3. — Al Kα and W Mα, β spectra obtained with a HRXMM and the corresponding MIM. The features of the devices are given in the text.

\[ d = 2.4 \text{ nm} ; \quad \text{HRXMM} : \quad D = 1 \mu m ; \quad \Gamma = 0.16. \] The improvement in resolution is very spectacular, thus the spectral bandwidths of Al Kα are about 15 and 50 eV when analyzed with the HRXMM and the MIM respectively. Note the difference between the positions of the lines diffracted by the MIM and the HRXMM arises from a modification of the average refractive index induced by the etching. Indeed the efficiency of the zeroth order of a LMA can be calculated in first approximation [5] as the reflectivity of a homogeneous medium whose refractive index is averaged by the proportion of multilayer medium with respect to vacuum. A modification in the value of this average refractive index affects both the peak efficiency and the angular position.

Neither the nominal nor the effective characteristics of the HRXMM are optimal, so that at the view of these first results, the HRXMMs appear as promising tools for highly resolutive X-ray spectroscopy.

3. X-ray polychromator.

The purpose of this device is to spatially split a polychromatic beam into several quasimonochromatic beams. The principle of the device was given in a paper by André et al. [8]. It is based on the unique property of the LMA mentioned in section 1. According to equation (1), for a given glancing angle \( \theta_0 \) at each diffraction order \( p \) of the LMA corresponds a wavelength \( \lambda_p \) satisfying this equation. The radiation of wavelength \( \lambda_p \) is emitted at an angle \( \theta \) with respect to the surface given by the grating law

\[ p \lambda_p = D [\cos \theta - \cos \theta_0]. \] (2)

The spectral bandwidth of each quasimonochromatic beam is governed by the same conditions as those mentioned for the HRXMM and the angular splitting is conditioned by the grating period \( D \). Using the synchrotron radiation provided by the Super-ACO storage ring facility, we have experimentally evidenced the features of this « polychromator » in the 800-1300 eV energy range [7]. The experiment is conducted as follows (see Fig. 4).
Fig. 4. — Experimental layouts for the study of the performances of the « polychromator ».
i) By help of a double-crystal monochromator equipped with beryl crystals, one illuminates the « polychromator » at a given glancing angle $\theta_0$ and one scans the detector to follow a given order $p$. This operation gives the energy calibration, the energy efficiency and the selectivity of the system.

ii) One illuminates the « polychromator » for the same glancing angle $\theta_0$ with a polychromatic radiation and one records the diffraction pattern.

A typical diffraction pattern recorded through a « 5 $\mu$m Al + 16 $\mu$m Be » filter, is shown in figure 5. The characteristics of the device are:

MIM : 100 W/C bilayers ; $d = 4.12$ nm , $\gamma = d_w/d = 0.4$ ;

LMAG : $D = 1$ $\mu$m , $\Gamma = 0.09$.

![Diffraction pattern](image)

**Fig. 5.** — Diffraction pattern of a « polychromator » illuminated by the synchrotron white radiation. The features of the device are given in the text.


The purpose of the device is to focus an X-ray beam in a line whose widths is of the micron order. The principle of this kind of optics was given by Aristov et al. [9] : basically it consists in combining the Fresnel and the Bragg diffractions. This lens is obtained by etching a
multilayer structure according to the pattern of a linear Fresnel zone plate. One distinguishes the positive and the negative BFLZPs whose definitions are given by the figure 6. We have measured [10] in the conical configuration (i.e. the lines are parallel to the direction of the X-ray beam), the performances of a positive and a negative BFLZP with the following features: MIM : 25 W/Si bilayers, \( d = 5.3 \) nm, \( \gamma = d_w/d = 0.4 \).

BFLZP: \( a = 11 \) \( \mu \)m , outermost zone width = 0.4 \( \mu \)m ;

dimension = 210 \( \mu \)m

![Fig. 6. — Topview of a Bragg-Fresnel linear zone plate (BFLZP). For the positive BFLZP, the black bars correspond to the multilayer structure while the white bars correspond to vacuum. The opposite situation occurs for the negative BFLZP.](image)

The incident radiation is the white beam provided by the Super-ACO storage ring. The data are recorded by using a gas detector collimated by a 13 \( \mu \)m pinhole and high resolution holographic plates (2 000 1/mm). In first approximation, the theory gives the focusing distance \( r_p \) as

\[
r_p = \frac{a^2}{p\lambda}
\]

where \( p \) is the order of focusing. Note that a refined geometrical theory of the BFLZP diffraction [11] gives a more accurate relationship between the distance \( r_p \) and the geometry.

In our conditions (Bragg angle = 4° ; \( \lambda = 0.71 \) nm) one has \( r_1 = 162 \) mm. Figures 7 show the angular distribution of the diffracted radiation in a direction perpendicular to the specular direction, for different distances of the detector with respect to the BFLZP. The focus line width measured in the first order focal plane using the holographic plates is less 15 \( \mu \)m which
Fig. 7. — Experimental and theoretical diffraction patterns of positive and negative BFLZs whose features are given in the text.
Fig. 7 (continued).
corresponds to the source size with the demagnification of our experiment (0.01). The experimental curves may be compared to the theoretical spatial distribution calculated in the framework of a dynamical theory [12]. The agreement between experiment and theory is fairly well especially concerning the lack of background beyond the first focus for the negative BFLZP.

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