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BRAGG-FRESNEL OPTICS AND SUPERMIRRORS

ABSTRACT

The main principles and some applications of Bragg-Fresnel multilayer optics and X-ray supermirrors are described. An elliptical Bragg-Fresnel multilayer lens (BFML), designed and fabricated in the IMT RAS has been used for 2-dimensional focusing of the white X-ray synchrotron beam. For the beam energy of about 12 KeV the spot size checked with the knife edge method was about 1μm. Applications of BFML and supermirrors in x-ray imaging are discussed.

1. INTRODUCTION

The present-day stage of developing new optics for x-ray beams calls for creating effective focusing elements with the structure of three-dimensional Fresnel zones: Bragg-Fresnel optics. Multilayer mirrors and crystals are the basis for such elements. These structures are the first elements of microphotonics as they allow for transforming the information of electrical, optical or acoustic signals into X-ray beam modulation.

In 1963, Yu.N. Denisiuk published an idea to use a combination of volume Bragg diffraction and Fresnel or Fraunhofer diffraction for recording and reconstruction of optical holographic images [1]. The first proposal for the application of this technique to X-ray focusing was done by V.V.Aristov [2]. In this new kind of X-ray optical system, a crystal or a multilayer acts as the Bragg reflector. Experiments were done using both kinds, ion etched crystals [3] and multilayers [4,5]. In principle Bragg-Fresnel multilayer lens (BFML) keeps the advantage of the Fresnel zone plates, which offers a high spatial resolution when used in transmission. The use of multilayer static and dynamical gratings is also very promising [6,7].

2. BFML DESIGN

A perfect BFML is a 3D system of isophase surfaces reflecting an interference pattern of a divergent spherical wave from a point A_1 (source) to a convergent spherical wave in point A_2 (image) [8]

For a wavelength λ, reflected to point A_2, the distance between the successive surfaces is such that a path difference is a multiple of λ.

To obtain 2D focusing with a flat Bragg reflector, one needs to produce a volume structure as indicated schematically in fig.1. In fact, due to the limited penetration depth of the X-rays, the multilayer structures we used can have a rectangular profile. Fig. 1 show formation of 3-dimensional Fresnel zones.

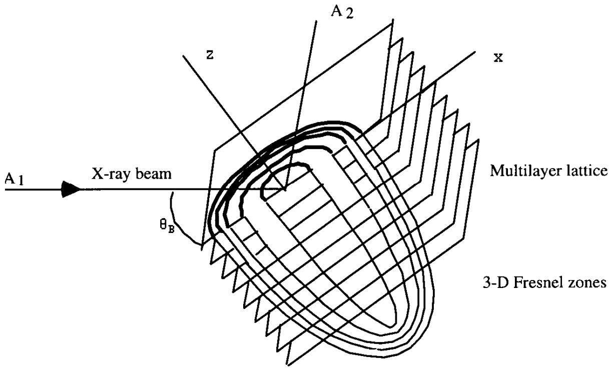

Fig. I Three-dimensional Fresnel structure of the BFML lens.

In our experiment we used a multilayer W/Si and W/C mirrors prepared by magnetron sputtering on a thick super polished silicon wafer and period spacing of the bilayers in the range about 2.5nm - 3.5nm. A number of bilayers of the order of order of 60-100 were prepared, an experimental multilayer reflectivity 60%-75% at 0.154 nm was measured.

To provide two-dimensional point focusing the special designing and fabrication of elliptical BFML were done.

Electron beam and optical lithography, ion-beam etching processes are successively employed to obtain a BFML. In our laboratory a ZRM-12 electron-beam instrument with the modified computer control system have been applied for the generation of an elliptical-shaped topology of a BFML. The hardware as well software for the IMT RAS exposure system was developed to provide topology fabrication of a complex optical elements. Linear spline approximation of the analytical diffraction lenses formulas have been used for exposure data preparation. Recently a new software being developed provide also correction of the scan field distortion and can be used for the fabrication of optical elements in large fields [9]. Special attention for the structure fabrication accuracy have been paid. Software for exposure data acquisition includes the experimental parameters of exposure field distortion. The RF-excited argon ion-beam source for the BFML structure etching in multilayer depth was used.

To avoid a scattering from the mirror around BFML the second lithography-etching procedure were performed through the special aperture mask. The aperture mask was patterned in a layer of Fe_2O_3 on a glass substrate by electron beam lithography and wet etching. Then we used this mask for UV lithography on the multilayer coated with photoresist. Finally, we etched the multilayer down to the substrate through the photoresist mask by using the same RF-excited ion-beam source.

The typical BFML, designed for 12.4 KeV radiation shown in the fig.2. This lens prepared on a 60 bilayer 3.2 nm period W/C multilayer mirror coated by magnetron sputtering (prepared by A.Yakshm, IMT RAS). An ALCATEL SCM-651 coating system was used for the multilayer preparation.

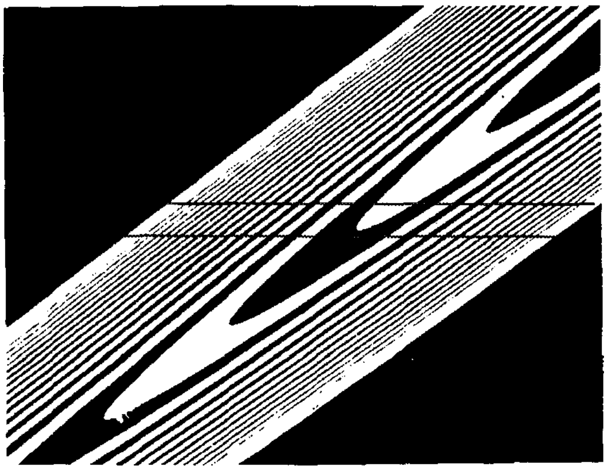

Fig.2 Microphotograph of the elliptical BFML, general view.

3. BFML RESOLUTION AND EFFICIENCY

The main limitations of BFML resolution are due to technological parameters and aberrations. Existing technology limits a minimum zone size about 0.1 μm. Aberrations are more serious especially at a small angle of incidence.

To analyze the off-axis aberrations, one can use an optical path difference assuming a rectangular groove profile. Using the optical path representation it is possible to find the analytical expression for main off-axis aberrations: coma, astigmatism and field curvature. According to the Rayleigh criterion, angle of view, limited by coma, astigmatism and field curvature is equal to:

$$\alpha_{coma} = \frac{\Delta r_{\min}^2}{\lambda F}\left[\frac{\lambda}{4\Delta r_{\min}\left(1+\frac{\lambda}{2\Delta r_{\min}}\cot\Theta_B\right)^3} + \frac{\cot\Theta_B}{1+\frac{\lambda}{2\Delta r_{\min}}\cot\Theta_B}\right]^{-1};$$

$$\alpha_{ast,f.cur} = \left\{\frac{\Delta r_{\min}}{F}\left[\frac{3\lambda}{4\Delta r_{\min}\left(1+\frac{\lambda}{2\Delta r_{\min}}\cot\Theta_B\right)^3} + \frac{\cot\Theta_B}{1+\frac{\lambda}{2\Delta r_{\min}}\cot\Theta_B}\right]^{-1}\right\}^{1/2}$$

where $\Delta r_{\min}$ is the minimum zone size;
F is the focal length;
Θ_B is the Bragg angle.

As an example, the field of view of the BFML lens characterized in the Table I is shown in the fig.3. This lens when used at the angle of incidence of 0.955° has view angle of about 12 μrad in one direction. Those parameters were chosen to demonstrate the importance of Coma aberration at small angles and Field Curvature domination close to normal incidence.

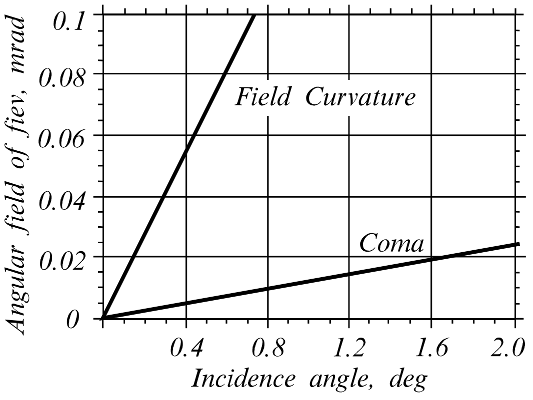

Fig.3 Angular field of view of an elliptical BFML in plane of diffraction. Minimum zone width 0.25 μm.

Photographic resolution tests were performed for the fixed beam energy of 12.4 KeV, at the experimental set-up, installed on the DCI storage ring (LURE, Orsay (France)). High resolution (0.1 μm) VRE type photographic plates made in Russia have been used to test the spot configuration. Fig.4a shows the corresponding 3-D plot of the 50 μm 42 times reduced pinhole image. The best value of the observed focus spot was about 1.3 μm in diameter.

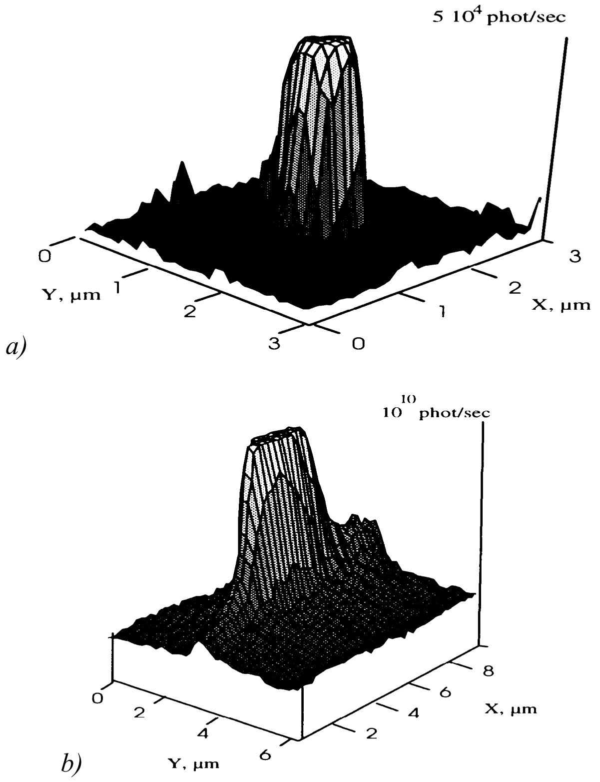

Fig.4 3-D scan of the focal spot obtained by the elliptical Bragg-Fresnel lens using white collimated beam with 50 μm input pinhole at DCI (a) and uncollimated undulator beam at ESRF (b).

The optimal depth of the lens profile has been calculated according to the following ideas. The most zones, occupying the large area of the zone plate, have a lateral period larger, than the extinction length, L_{ext}, of the multilayer mirror, equal to ~ 10 μm for the particular multilayer and the Bragg conditions. L_{ext} is equal to extinction depth divided by the $\sin\theta_B$. In this case the beam reflects mainly inside of the one period of the grating and an ordinary diffraction on the thin grating takes place producing a several diffraction orders inside the Bragg peak simultaneously. One can estimate the optimal profile depth corresponding to the maximum of the first order diffraction efficiency [7]. In the case of an amplitude-phase lens the efficiency can be evaluated by a simple formula proposed by Kirz [10]:

$$\frac{I_1}{I_0} = \frac{R\left[1+\exp(-\chi\pi)\right]^2}{\pi^2}$$

where χ value is:

$$\chi = \frac{\beta_W T_W + \beta_C T_C}{\delta_W T_W + \delta_C T_C}.$$

Our multilayer mirror, having a reflectivity R=0.7, would lead to a first order efficiency of roughly 0.25, if our BFML was similar to a classical amplitude-phase grating. Experimental efficiencies in normalized units: the ratio of the focused energy to the total energy reflected on into a 20 μm output aperture of the BFML were found to be 1670 at 12.4 KeV and 1070 at 8.3 KeV. This value is in agreement with the theoretical prediction mentioned above for a classical amplitude-phase grating. This indicates the phase character of the obtained diffraction.

The number of photons experimentally obtained in the focal spot in the LURE test was on the order of $5x10^4$ phot/sec [11]. Much better flux was obtained in the experiment at the European Synchrotron Radiation Facility (ESRF) [12]. In the fig.4b is shown of about 400 times reduced image of the undulator source at the ESRF "Troika" beam line. This experiment confirms a high radiation stability of BFML. Photon flux in order of 10^{10} phot/sec in a focal spot of 2.5μm x 5μm in size was obtained.

4. BFML APPLICATIONS: X-RAY MICROPROBE

Designing an X-Ray microprobe on the basis of BFML seems one of the most promising applications of such a lens. The preliminary design of a fluorescence X-Ray scanning microprobe with submicron resolution was tested at the LURE (France) facility in 1992-93 [13,14]. An elliptical multilayer Bragg-Fresnel lens has been used for focusing of the white x-ray synchrotron beam at beam energies of 12.4 KeV and 8 KeV.

High sensitivity of the fluorescence microprobe analysis was demonstrated in the experiment, made on an undulator at the ESRF facility in 1994 [12]. For that purpose tests were performed with a specially prepared object: Cr photomask of 80 nm thickness deposited on a glass substrate. With this sample the count rate on $Cr_{K\alpha+\beta}$ was of the order of 700 per second for an electron beam intensity of 100 mA. Considering the detectors efficiency and absorption this means that up to $2x10^9$ photons were concentrated in the focal spot. Moreover it was measured, that it is possible to increase flux by 5 times by changing the gap to the maximum of the undulator harmonic.

5. X-RAY SUPERMIRRORS

BESSY-11 will provide not only VUV photon beams applications, but also some relatively high energy beam lines, up to 50 KeV. Thus, the need for hard x-ray optics has become considerable. For some applications especially as a first beam line mirror the band-pass of crystals and periodic multilayers is too narrow. A wider band-pass can be obtained using total external reflection from heavy elements. This possibility, however, is impractical for hard X-rays (>20 KeV) because of the extremely small value of the critical angle for total reflection. One to produce broad-band reflection may be with supermirrors, well-developed for neutron optics: a multilayer structure, where the bi-layer thickness is gradually changed from top to bottom [15]. But compared with neutrons, where absorption is very low for most materials, X-rays have relatively high absorption coefficient and the principles for designing of neutron supermirrors cannot be directly applied in the x-ray region. However a successful example of x-ray supermirror fabrication has been reported recently. There the capability of bent supermirrors to focus X-rays at high energies was demonstrated. The W/Si supermirror showed reflectivity of more than 30% for energies up to 65.5 KeV[16].

In our case the band-pass of a supermirror must cover the energy range from 2 KeV to 20 KeV. We found it impassable to use the same principle in this energy range as for high energy photons. Due to very high absorption, the number of layers constructively involved in interference is much smaller than for higher energies. This leads to dramatic oscillations of spectral reflectivity. The solution was found by combining the total external reflection from the top layer of a heavy material and the interference reflection from a multilayer with variable period in the bottom. The structure of such a multilayer shown in the Fig.5.

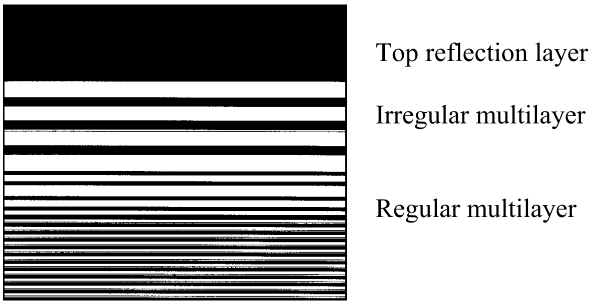

Fig.5. Structure of the supermirror

First, from substrate to the top, a regular multilayer with period corresponding to the highest reflected energy is deposited. Then a multilayer with variable period is generated and finally a thick layer of heavy material is deposited. This layer provides reflection from the low energy edge of the spectrum. In figure 6 one can see calculated characteristics of such a mirror, designed for the energy range between 5 and 21 KeV.

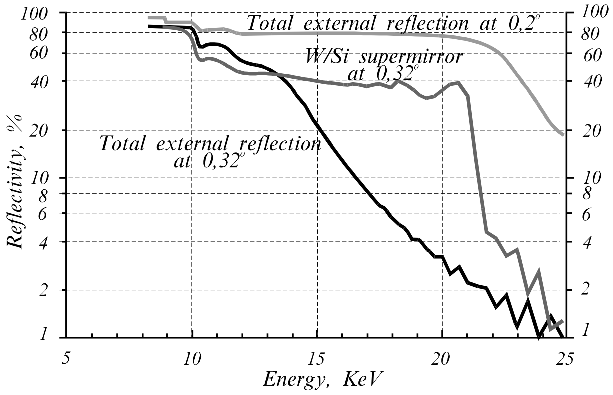

Fig.6. Supermirror reflectivity

Over the entire calculated energy range the supermirror reflectivity exceeds 35% with oscillations of about 10%. In the same figure, the total external reflection curves at 0.2° and 0.32° are also shown.

CONCLUSIONS

A number of different types of BFML have been tested on the Del synchrotron source as well as ESRF performing a 2D focusing. At the Del synchrotron source the beam has been collimated so as to check the spatial resolution limit. Imaging of specially prepared test objects has been achieved at between 8 and 12.4 KeV on photographic plates, transmission and fluorescence tests have been successfully performed. These measurements confirm that the theoretical spatial resolution can be obtained with the present multilayer and BFML technologies. The supermirror in this example is only 0.6 as long as total external reflection mirror with the same spectral response.

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Bragg-Fresnel optics and supermirrors

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