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X-UV INTERFERENTIAL MIRRORS AND NEW POSSIBILITIES FOR PLASMA RADIATION STUDIES

P. DHEZ

Laboratoire de Spectroscopie Atomique et Ionique and LURE, Université Paris XI, F-91405 Orsay Cedex, France

RESUME

La réalisation de miroirs interférentiels adaptés au domaine X-UV est une possibilité apparue seulement depuis une dizaine d’années. Dans une première partie nous rappelons les caractéristiques principales de tels miroirs. Par comparaison avec les optiques sous incidence rasante seules disponibles jusqu’à maintenant, nous indiquons ensuite les nouvelles voies ouvertes par leur utilisation. Enfin nous donnons quelques exemples de diagnostic de plasma tirant partie de ces nouvelles possibilités.

ABSTRACT

For about ten years new multilayered X-UV mirrors have been in progress and are now overcoming some of the main difficulties well known with the grazing incidence optics used up to now. The main characteristics of such mirrors are first recalled. Next some of the new possibilities in X-UV spectroscopy and imaging are given. Finally we briefly describe some examples of new set ups using such X-UV interference mirrors for plasma diagnostic.

INTRODUCTION.

Several papers at this first colloquium about "X-Ray Laser" demonstrate clearly the importance of plasma diagnostics to progress in the understanding of the mechanisms leading to the population inversion and how the use of the X-UV range is well suited to study plasma temperature, density and characteristic lines of highly ionized atoms. Indeed, the progress in such diagnostics using spectroscopy or imaging optics are very dependant to the possibilities to build the corresponding X-UV optical systems to achieve them.

Until now, most of the set ups have been restricted to grazing incidence and cristal optics (1). This is due to the X-UV optical constant values. Over all the X-UV range, these one forbid at the same time the classical normal incidence mirrors with single interface, which need very absorbing material, and also the refractive lenses, because refractive index is too close to the vaccuum one. The quite recent development of multilayered mirrors (2) and Fresnel zone plate (3) had considerably enhanced the possibilities to conceive X-UV optics better adapted to X-UV diagnostics. Based on diffraction properties, such interferential optics are not similar to the classical single interface mirrors and refractive lenses well known in the visible range. To get such X-UV diffracting optics, special microfabrication technologies have been recently developed. The present state of art in this new field permits to overcome several limitations which up to now had slowed down the use of the X-UV range.

In this paper I will try first to recall the basic properties of the X-UV interferential mirrors. Next I will indicate new possibilities offered by such mirrors to design new X-UV optics. Finally I will give some examples of new plasma diagnostics using these interference mirrors.
Before to come to interference mirrors, let us first remember how the classical single interface mirror acts.

The first figure shows how the absorption coefficient of gold is linked to normal incidence reflectivity (4). Because, in the X-UV range, all materials have almost the same order of magnitude for the optical constants, they all exhibit the same behaviour. Fresnel formula gives the reflectivity coefficient versus the angle of incidence permits to calculate the efficiency of X-UV mirrors by using X-UV optical indices (5).

Figure 2 is an example of such calculations for a hafnium dioptré at three wavelengths (6). It demonstrates how reflectivity decrease with absorption coefficient when wavelength becomes shorter and how a noticeable reflectivity regime is restricted to grazing angle range. Some physics text books explain that only an infinitely absorbing material is a perfect mirror.

In such case, almost all photons are absorbed by the first atomic layer and immediately reemitted, so they look like reflected.

In actual materials, photons penetrate the medium. The penetration length usually considered in such problem is the thickness \( \frac{1}{e} \) of the incident intensity, about 0.3.

Along the penetration path most of photons are absorbed, converted in heat or photoelectrons, and those reemitted suffer also absorption on the back way before they leave the mirror. As a rule, good normal incidence mirrors are obtained only from materials having a penetration length smaller than, or comparable to, the wavelength of the light to reflect.

As indicated by curves on figure 3, no material satisfy this condition in the X-UV range. So, according to Fresnel formula only grazing incidence works in this range for dioptré mirrors.

Dielectric mirrors for visible are stacks of very transparent materials, containing alternating equal thickness of high and low index transparent materials. It is a first example of interferential mirrors using a penetrating wave. Such a principle looks very convenient to the X-UV range where we cannot avoid the wave penetration. In the case of transparent materials, each interface is only slightly reflecting, due to the weak difference between the index of both materials.
At the end, one get a constructive interference for the wavelength corresponding to the difference of optical path between the successive partial waves. By this way 100% reflectivity can be obtained with non absorbing media.

Another model of efficient interferential mirror is the ideal Bragg crystal containing very thin layers of a perfectly absorbing material set at a regular distance in a perfectly transparent medium. Real crystals are not like that, but atomic planes bring a periodic electronic density modulation which also works conveniently. More than that, crystalline materials are not an absolute necessity. In fact, as remarks very earlier, thin amorphous evaporated layers can in principle leads to a more convenient electronic density modulation, if qualities of the interfaces can be controlled.

In summary the common point to these both kind of interference mirrors working with a penetrating wave is the need of a periodic medium with a d period matching the classical Bragg's law: \(2d \sin \theta = \lambda\).

Let's turn now our attention to the efficiency of such interference mirrors. Calculations show that, even with slight absorbing materials, the efficiency of such systems decrease very fast and by consequence are both inefficient in the X-UV range. E. Spiller have been the first to clearly point out that with absorbing materials one can still get noticeable reflectivity with interference mirror (7). In this case, one must build evaporated periodic layers containing a first material with the maximum absorption at the desired wavelength as an efficient scatter and a second one the more transparent as possible used as a spacer. In addition one must to adjust the relative thickness of the more absorbing material in such a way that reflectivity per period is larger than its absorption. How to adjust this relative thickness, called \(p\), and how much reflectivity can be obtained have been next summarized on a simple graph by A. Vinogradov (8), in the case of purely absorbing materials. Such an approximation is quite valuable for the X-UV range. For more precise calculations one must take into account the refractive part of the index, which leads to an increase of the reflectivity.

In the case of the W/C couple of material, figure 4 shows the maximum of the normal incidence reflectivity which can be obtained, even by optimizing the \(p\) parameter for each wavelength (9). Due to the quite high absorption, just before the CK edge around 44A, the carbon appears clearly as a bad transparent material in this range. Actually, such edges are also present in the reflectivity curves of any natural or organic crystals, for example on OK around 16A. So, to get the most efficient interferential mirrors along all the X-UV range one needs to choose the most appropriate materials for each range. Such a search have been done by A. Rosenbluth (9) during his thesis and the computerized results are given in figure 5.
The vertical lines indicate where new couple of materials must be used to keep the maximum normal incidence peak reflectivity. The optimum parameter \( \beta \) and the necessary number of periods \( N \) to get such reflectivity are given.

Considering a given wavelength and changing slightly the \( \beta \) parameter offer two interesting possibilities.

The first one is to optimize the multilayers for maximum peak or integrated reflectivity, or for the best resolution (10). The second one is to minimize the overlapping order. The figure 6 is an example of calculation for the case of W/C multilayer at 8Å (11). With a small decrease of reflectivity it is possible to minimise at the same time the second and third order. Around \( \beta=0.5 \) we got the equivalent of a centrosymmetric cell well known in diffraction system as able to cancel all the even orders. An experimental check of these possibilities have been done (11) and the damping of any chosen order has been observed.

It is not here the right place to give details about calculations, evaporation and testing methods developed to obtained good X-UV multilayers mirrors. Let us just say that presently, results obtained in different countries are very encouraging, a recent meeting specially devoted to X-Ray Multilayered Optics (12) can be considered as a good summary of the present state.

Two examples of reflectivity curve are just given here to illustrate the results.

Figure 7 illustrates some peculiarities of such mirrors working in fact with few periods compared to a crystal. The reflectivity curve versus the incidence angle has been got with the 1.54Å CuK line and a 12 periods W/C multilayers \( 2d=120A \) (13). One can see the total reflectivity range for the most grazing incidence range and next the Bragg peaks corresponding to the \( N = 1, 2 \) and 3th order of the classical Bragg formula \( 2d \sin \theta = N \lambda \). Secondary maxima between two successive Bragg peaks are similar to those observed in the multislit experiments in visible with a small number of diffracting objects. So, adding 2 to the number of observed secondary maxima gives the number of working periods of the mirror. When a fixed angle of incidence is used and the band pass of the multilayer is registrated versus wavelength, such secondary maxima can also been observed on each side of the reflectivity peak.
The figure 8 shows the reflectivity observed on the copper emission lines (La,β) at 13.2Å with an organic crystal, lead stearate in this case, and a 21 periods W/C multilayer prepared with almost the same 2d. Such a direct comparison demonstrates that optimized multilayers can be much more efficient than organic crystals (14) for integrated and peak reflectivity. Especially optimized multilayer for a given wavelength can be more efficient than this one. The resolution of the multilayers is lower due to the small number of layers.

NEW POSSIBILITIES GIVEN BY X-UV MULTILAYERS

Several new ways to design multilayered optics have been tested. In addition of the possibilities to optimize such mirrors for any wavelength at any choosen incidence, including the normal one, we can obtained more efficient and more stable layers under high flux than with organic crystals. Stability of multilayers under high pulsed X-ray burst begin to receive attention for plasma diagnostics (15).

As suggested by several people, it is possible to prepare multilayers with a gradient of the period along one direction. Keeping fixed the incident angle and moving such multilayer along the graded direction in front of an X-UV beam will change the reflected wavelength. So without any change in the incidence angle, the equivalent of a double monochromator can be obtained by using a single translation and two parallel multilayers (16). More recently it has been proposed to use such graded multilayer on point to point focusing optics toroidal mirrors. Changing the period d locally as desirated leads to enhance the reflectivity or to restrict the band pass of the focused beam (17).

Figure 9 shows a proposal to obtain quasi normal X-UV efficient grating (10). Reflectivity would be obtained by the multilayer and dispersion by the grating. Obviously for a choosen wavelength it is necessary to match the blaze angle and the groove distance of the grating with the multilayer period. In fact not only the echelette grating but any kind of groove shape can be used, as demonstrated by recent electromagnetic theoretical calculations on such layered gratings (18).

Another way opened by multilayers is the possibility to build X-UV polarizers and polarimeters. Like in others electromagnetic range, the use of the Breswter angle permit
to reflect only one of the component of light and so to polarize a beam by reflection. That happens for the incidence angle such that the refracted and the reflected direction of the wave are at 90°. Because refractive index is almost the unity over all the X-UV range, the 45° incidence provide always a very good polarization rate as appears on the figure 2. Unfortunately, such a possibility is forbidden with classical single interface mirrors because for such large angles the reflectivity efficiency is too low. On the contrary, a multilayer optimized for such incidence can have good reflectivity and so to be an effective polarizers. Possibilities of X-UV polarizers and polarimeters have been demonstrated recently (6, 19).

Multilayered optics being able to work at the normal incidence, is in principle possible to return to the well known optical system using normal incidence mirror for telescope or microscope. Such possibility have been first tested at 44.4A with a spherically bended silicon wafer previously coated with a multilayers (20). Schwarzchild microscope with two spherical confocal mirrors have been next designed for synchrotron source (21). Another example of imaging multilayered optics is the telescope built at the Institut d’Optique d’Orsay for the french astrophysicists (22). It is a Ritchey-Chretien type system where aspherization of the first mirror have been achieved by a graded single layer evaporated on the spherical blank before the multilayer coating (23).

X-ray Fabry-Perot, first demonstrated by T. Barbee, is an other major advance which must be underline (24,25).

EXAMPLES OF THE USE OF MULTILAYERS FOR PLASMA DIAGNOSTICS

Figure 10 shows the principle of the system designed by the Livermore group to receive simultaneously on the same streak camera photocathod several small band pass of the spectrum emitted by a laser plasma (26). It is certainly the first system taking advantage of the multilayer possibilities, in this case to choose freely the 2d spacing. By this way they can work at the Bragg condition for different choosen wavelengths, but with the same Θ Bragg angle.

Imaging of plasma with grazing incidence Kirkpatrick’s mirrors or pinhole camera optics have always been limited by the difficulty to select a small band pass of the spectrum passing through these optics. Metallic filters are very inefficient in the X-UV and multilayers appear as a good solution for such filtering. Such a band pass selection for X-UV pinhole camera had been used at the PMI Laboratory for laser plasma imaging. A metallic filter is just added to protect the multilayers from the plasma burst but also to block the visible and UV which would be reflected by the multilayers. With such a system, images of aluminum ions emitted at 154A have permitted to compare the lateral expansion of the plasma for the ω and 2ω frequency of the laser (27).
Combining a flat and a focussing multilayers with matched periods, the same group of the PMI laboratory also achieved the first demonstration of the possibility to experimentally evaluate in X-UV the refractive index of laser produced plasma (28). The scheme of the set up is given on figure 11.

One part of the laser beam produces the X-UV probed plasma. The 45° flat multilayered mirror was optimized to reflect only the 154A for which they wish to test the refractive index. No strong line of this wavelength is emitted by the probed plasma. A parallel beam of the desired wavelength, a strong 154A line emitted by a Cu target, is selected and reflected in a parallel beam by using another spherical multilayered mirror. Only this parallel beam after refraction through the plasma produces a spot on the photographic plate, and the measured deflection has been used to evaluate the refractive index.

Direct imaging of plasma by large angle collecting optics is an other possibility open by normal incidence spherical optics, with the additional advantage of magnification. A Schwarzschild microscope have been recently built at the Institut d'Optique d'Orsay for the PMI Lab to obtain X-UV image at the rear surface of a foil in view to study the heat transport inside the target during the plasma formation. Results obtained at 304A with a 6μ spatial resolution during the first trials look very promising (29).

X ray laser research, which began in the seventies (30) is an other field where multilayers can be helpful, even if a complete resonator is not yet working. As proposed in 1982 by our group (31) and demonstrated last year at Princeton (32), a single normal incidence multilayer mirror set in normal incidence can reflect enough intensity through the plasma column to produce a noticeable intensity change on the tested line.

The figure 12 shows the predicted effect with an achievable mirror reflectivity and observed gain plasma amplification in our experiment (30). Because no change in the spectrum can appear outside the reflected band pass of the mirror, a comparison between shots, with and without mirror, is straightforwad. In addition, the relative line intensities over the unchanged range give good information about the laser shot and helps for statistical errors evaluations.
Obviously the realisation of the second multilayer working in the semi transparent mode as an exit window of an X-UV laser is a very exciting problem. Another talks in this meeting will review the questions and the state of art on this field (32,33).

CONCLUSIONS

Limitations brought by the obligation to build only X-UV grazing incidence optics are now removed after a long sixty years history. The quite recent X-UV multilayer mirrors bring completely new possibilities for X-UV optical systems. Some examples of uses, summarized here are just a first blooming of applications. As when a new tool arrives, we are just presently solving the first class of problems which are the most stringent in our work and which look the easiest. No doubt that this new allowance to conceive X-UV optics, with large collecting aperture and working at the same time as an efficient band pass filter over all the range, will lead to a large diversity of systems helping the plasma diagnostics. We have not yet all the equivalent optical systems of the visible range, but this step ahead with interference mirrors have reduced the gap which separates the X-UV optics of the numerous possibilities available in other ranges.

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