Development of non-periodic multilayer in the EUV, soft X-ray, and X-ray ranges

Zhanshan Wang (王占山)*, Jingtao Zhu (朱京涛), Baozhong Mu (穆宝忠), Zhong Zhang (张 众), Fengli Wang (王风丽), Xinbin Cheng (程鑫彬), Fangfang Wang (王芳芳), and Lingyan Chen (陈玲燕)

Institute of Precision Optical Engineering, Physics Department, Tongji University, Shanghai 200092, China

**E-mail: wangzs@tongji.edu.cn*

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A recent development of mirrors is reviewed in this letter. For some applications, such as the hard X-ray telescope, polarization measurements in synchrotron radiation facilities, extreme ultraviolet (EUV) solar observations, and dense plasma diagnostics in China, a series of non-periodic novel multilayers with special performance are developed. X-ray supermirror, EUV broadband polarizer, EUV wide-angular mirror, and double period Kirkpatrick-Baez (K-B) mirror are successfully designed by using different multilayer stack structures.

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Multilayer coatings have been widely used as key reflective elements in extreme ultraviolet (EUV), soft X-ray, and X-ray ranges. In the early years, periodic multilayer coatings were utilized as reflective mirrors in astronomical observation, X-ray lasers etc. at synchrotron radiation facilities and dense plasma diagnostics, particularly in the soft X-ray region[1−4]. Except for normal periodic multilayer coatings, there are some special requirements which are not met by just using periodic multilayer coatings in some applications, such as broadband width, wide angular, and multi-function mirrors. In this regard, non-periodic multilayer coatings have been developed for these cases. Development of thin film deposition techniques has made it possible to fabricate highly precise multilayers with lateral d-spacing variations necessary to significantly improve the overall reflectivities of these mirrors. Combining non-periodic multilayer coatings with special substrates, X-ray optical elements with beam-shaping properties have become possible. Today, non-periodic multilayer coatings are increasingly being used. This paper summarizes the recent developments in non-periodic multilayer coatings for applications in X-ray telescope, EUV polarimetry, X-ray microscope, and dense plasma diagnostics.

The key to design non-periodic multilayer coatings is the selection of merit functions, optimized algorithms, and initial structures. The selection of merit function depends on the requirements of non-periodic multilayer coatings. Different applications need different merit functions. After the selection of merit function, optimized algorithms need to be chosen[5−8]. Three algorithms, simulated annealing algorithm, random search algorithm, and local optimization algorithm, are used. When the local optimization algorithm is selected, the initial structures of multilayers are very important as they decide how satisfactory the obtained results are. Quarter wave periodic multilayer and multilayer stacks with a variety of periods are often used during optimization. Moreover, the initial solutions generated by an analytical expression can be used in the most of the time.

Multilayer coatings were deposited by magnetron sputtering in vacuum systems at a base pressure below 10^{-4} Pa using Ar gas with purity of 99.9999% and a sputtering gas pressure of typical 0.2 Pa. Multilayers require the deposition of highly uniform thickness coating, so masks and varying rotation speed methods were used. The structures of the periodic and non-periodic multilayer coatings were characterized using X-ray reflectometry. The EUV and soft X-ray characteristics were performed with polarized radiation using the synchrotron reflectometer at BESSY II. The roughnesses of the substrate and the multilayer coatings were measured by using an atomic force microscope[9].

Supermirrors can provide a broadband reflectivity comparing with periodic multilayers. There are two kinds of supermirrors. One is the non-periodic multilayer which has a broad energy band at a fixed grazing angle, the other gives a broad angular band at a fixed X-ray energy. The supermirror is the key element for next-generation hard X-ray telescope. For easy measurement, supermirrors working at Cu Kα line (8 keV) were designed. Hence, most of our studies on supermirrors with a wide angular range were conducted using the Cu Kα line.

For special requirements of the angular interval at 8 keV, the simulated annealing algorithm was used to design a multilayer supermirror with two reflection bands to check the feasibilities of the design and fabrication of the supermirror. Figure 1(a) shows the designed and measured reflectivity curves of the W/C supermirror as function of grazing angle. Figure 1(b) indicates the thickness distribution of each layer in the supermirror multilayer, which results in a big layer thickness oscillation along the depth of the multilayer structure. This multilayer is prepared by using the direct current magnetron sputtering method. The difference between the designed and measured supermirrors depends on the achievable level of interface and roughness. Interfacial roughness and diffusion result from various materials and/or growth dependent mechanisms, including the interlayer formation by diffusion or by mixing due to

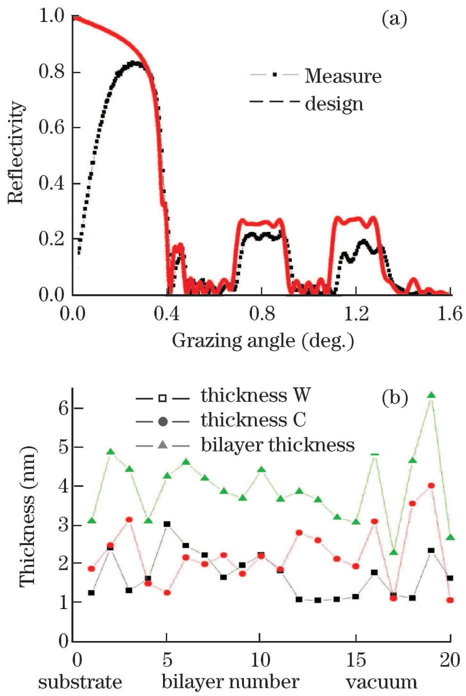

Fig. 1. (a) Design and measured reflectivities of the double reflection band W/C supermirror versus grazing angle, and (b) its layer thickness distributions.

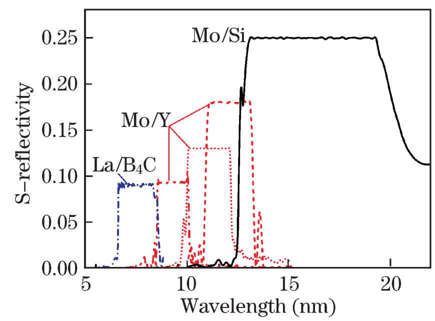

Fig. 2. Designed results of non-periodic multilayer analyzer with broad reflection band.

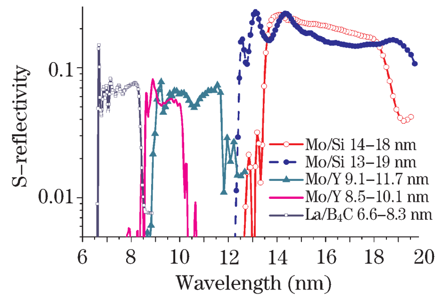

Fig. 3. Measured results of different non-periodic multilayer analyzers.

energetic bombardment during growth. Additionally, roughness results from low adatom surface mobility. Interface imperfections will reduce the reflection coefficients at the interfaces and increase reflection loss, thereby reducing the overall reflectance of the multilayer stack.

For polarization-sensitive studies, such as circular dichroism spectroscopy and spin-polarized photoelectron spectroscopy, accurate measurement of the polarization state of radiation is necessary, which requires polarization optical elements such as the analyzer and phase retarder. In the EUV region, periodic multilayers are commonly used in polarization when they are at the quasi-Brewster angle. However, because of the narrow reflection band of a periodic multilayer, the multilayers must be translated or rotated to perform broadband polarization analysis[10,11]. To simplify the experimental setup in EUV broadband polarization measurement, the broadband polarized elements using non-periodic multilayers have been proposed[12−17]. Using a non-periodic transmission phase retarder and a reflection analyzer, a complete broadband polarization analysis system can be developed. Various broadband non-periodic polarized components operating at different wavelength ranges and using different material combinations, such as Mo/Si (12.5–20 nm), Mo/Y (8–12 nm), Mo/B_4C (6.75–7.35 nm), and La/B_4C (6.72–8.32 nm), have been successfully realized in our experiment.

Several non-periodic multilayer reflection analyzers with different bandwidths and different material combinations have been designed and fabricated. Figure 2 shows the designed results which give a flat reflectivity in a definite wavelength range. Their spectral performance was evaluated by using a high precision 8-axes ultrahigh vacuum soft X-ray polarimeter on the beamline UE56/1-PGM-1 at BESSY II. Figure 3 shows the measured results. All the analyzers were designed at their Brewster angle near 45°. It is shown that the measured reflectivities are not very flat in all cases, which indicates the existence of deposition error and imperfect interface.

A non-periodic multilayer transmission phase retarder by using the Mo/Si combination has also been designed and deposited on Si_3N_4 membranes[16]. By incorporating the previously developed broadband reflection analyzer in the polarization measurements, this phase retarder was evaluated using a polarimeter on the beamline UE56/1-PGM-1 at BESSY II. The measured phase shift decreases from 55.6° to 38.1° with an average of 41.7±4.3° over the wavelength range of 13.8–15.5 nm. The transmission intensity was 2%–6% in the range of 13.5–15.5 nm with transmission ratio Tp/Ts of 0.96±0.11.

Using the developed non-periodic transmission phase retarder and reflection analyzer, we performed a complete broadband polarization analysis of synchrotron radiation for beamline UE56/1-PGM-1 at BESSY-II[17]. The polarization parameters of the radiation were also determined by least-squares fitting to the measured data. The fitted behaviors agree well with the model predictions of the circularly polarized radiation. The wavelength dependence of the polarization of synchrotron radiation can then be characterized by a complete polarization analysis without changing the incident angles of the broadband phase retarder and analyzer, thus resulting in the considerable simplification of such systems.

It is necessary to detect the emission flux of He^+ at 30.4-nm wavelength from the solar corona to evaluate its influence on the Earth's climate change. To meet this requirement, the desired non-periodic multilayer should have a special optical function, which provides high reflectivity at 30.4-nm wavelength covering a wide angular range from 68° to 78°. Figure 4 shows the designed, measured, and simulated results of the Mg/SiC non-period multilayer. The design is for non-polarization radiation emission from the solar corona, which has a flat reflection band at the desired interval. The measured results have a great difference from the design. After considering the incident light polarization produced by the synchrotron radiation light source, the measured curve agrees with the design one.

K-B configuration consists of two perpendicular concave spherical mirrors in tandem. The rays from the object point are reflected by the first mirror (tangential mirror) and form a tangential line, not a point. Similarly, the rays from the second mirror (sagittal mirror) form a sagittal line. Thus, the perpendicular structure plays an important role in overcoming the strong astigmatism. The K-B microscope is often used in dense plasma diagnostics.

The alignment of the K-B microscope is generally based on repeated X-ray imaging experiments. This operation has to be done in vacuum for a soft X-ray K-B microscope, so the experiments are very complex. To simplify the alignment, a double-period multilayer method is proposed. This multilayer consists of two parts stacked together with different periodic thicknesses. The top layer stack reflects the soft X-rays for imaging, while the bottom layer stack is designed for hard X-rays. Therefore, the X-rays of two different energies can be reflected at the same grazing angle. In this letter, the double period multilayer is developed, which includes W/B_4C top and W/B_4C bottom layers. As shown in Fig. 5, this multilayer has high reflectivity at grazing angle of 1.2° for both 4.75 and 8-keV rays. Thus, the alignment of

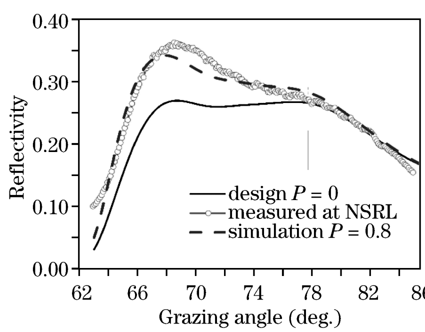

Fig. 4. Designed, measured, and simulation results of the non-periodic multilayer with a wide angular range at 30.4-nm wavelength.

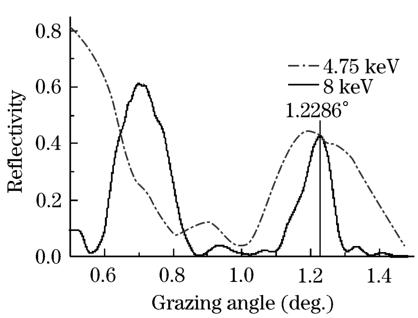

Fig. 5. Reflectivity of the double period W/B_4C multilayer designed both for $E = 4.75$ and 8 keV.

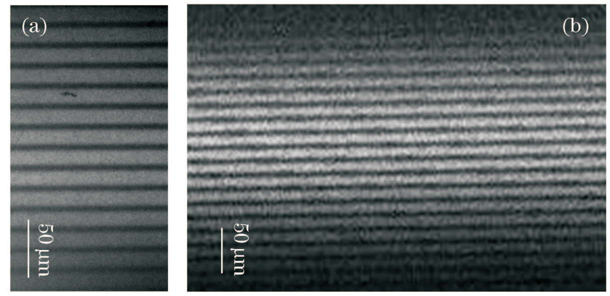

Fig. 6. Imaging results of the X-ray K-B microscope. (a) 8 keV in the air and (b) 4.75 keV in the vacuum.

4.75-keV K-B microscope can be realized in imaging experiments at 8 keV under air condition. Although the full width at half maximun (FWHM) of 8 keV is narrower than that of 4.75 keV, the accuracy of the alignment will be adequate enough. The imaging alignment results at 8 keV are shown in Fig. 6(a). The best object point was marked with a small ball, and the target was made at this same point using laser-induced plasma facility. The imaging results of 1,500 l/inch mesh at 4.75 keV (Ti Kα) are shown in Fig. 6(b). Hence, the double periodic multilayer provides a very practical method for the alignment of the soft X-ray grazing system in the vacuum.

In conclusion, a series of non-period multilayers are developed to meet the special requirement of some experiments in China, such as hard X-ray telescope, polarization measurements in synchrotron radiation facilities, and dense plasma diagnostics. All the multilayers are deposited by using magnetron sputtering method. A supermirror with double reflection band at the fixed energy of 8 keV is designed. In order to simplify the experimental setup in EUV polarization measurement, several broadband polarization multilayers are prepared covering a wide wavelength range from 6.7 to 20 nm. Using these non-periodic broadband transmission phase retarder and reflection analyzer, a broadband complete polarization analysis of the synchrotron radiation beamline is successfully developed. The double-periodic multilayer mirrors provide a very convenient method for the K-B microscope system in dense plasma diagnostics. The alignment of K-B microscopy system is performed in the air, not in the vacuum chamber.

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