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Reflection Passband Broadening by Aperiodic Designs of EUV/Soft X-ray Multilayers

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Abstract. By using three conventional optimization algorithms, we have developed computer programs of layer thickness designing for reflection passband broadening of EUV/soft X-ray multilayers. Three programs with optimization by Simplex, quasi-Newton and Gradient methods were found to be effective to search for aperiodic Mo/Si multilayers of a leveled reflectance of 35% within a wavelength region between 13 nm and 15 nm, though the thickness structures were considerably different. For much shorter wavelengths in the water window, solutions of Cr/Sc multilayers were also found for a leveled 30% reflectance between 3.14 nm and 3.16 nm, and also for a 15% reflectance between 3.13 nm and 3.17 nm. The bandwidth $\lambda/\Delta\lambda$ of these designs were improved from 286 of periodic multilayer to 137 and 66, respectively. Two practical design solutions were used to fabricate aperiodic Mo/Si multilayer mirrors by our ion beam sputtering system. The samples show EUV reflectance of more than 15% between 13 nm and 15 nm.

Keywords: multilayer mirror, optimization method, aperiodic structure
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INTRODUCTION

In the extreme ultraviolet (EUV) and soft X-ray wavelength regions, multilayer mirror optics are actively utilized for various normal incidence X-ray imaging optics. Particularly for the reflection at a wavelength of 13.5 nm, Mo/Si multilayer mirrors are adopted as projection optics for the next generation lithography tool [1]. At much shorter wavelengths of soft X-ray in the “water window” region between 2.4 nm and 4.4 nm, Cr/Sc multilayer mirrors were good candidates for biological and medical applications [2].

In these multilayer mirrors, several tens to hundreds layers should be stacked at high accuracy, which is inversely proportional to the number of layers [3]. Because of the large number of layers, the reflection peak is of a narrow bandwidth with $\lambda/\Delta\lambda$ being a few tens to hundreds. This causes difficulties to attain high throughput in the imaging optics composed of multiple multilayer mirrors since the error of period thickness control should be less than 1%, which is extremely difficult to achieve by deposition rate stabilization. To increase the tolerance of error, reflection passband broadening can be a practical solution.

Recently, Wang et al. successfully achieved the broadening with aperiodic structures of Mo/Si multilayers at a wavelength range between 13 nm and 19 nm by sophisticated computer routine [4]. The reflection passband broadening method is expected to be crucial not only for the wavelength matching but also for the spreading applications using EUV/soft X-ray multilayer optics. Thus, we have tried to use simple procedure with several conventional optimization algorithms [5] for the reflection passband broadening for our application of microscope development.

In this study, we briefly describe the procedure of computer designing with three commercial optimization algorisms for reflection passband broadening by aperiodic EUV/soft X-ray multilayer mirrors. Then we present the results of design examples at two wavelengths with theoretical reflectance spectra. Finally, experimental results of reflectance spectra of Mo/Si multilayer mirrors we fabricated with the designed thickness structure are shown for demonstration of a practical use.
PASSBAND BROADENING PROCEDURE

For computer simulation and designing of the EUV and soft X-ray multilayers, we have used Berning’s formula based on the Fresnel formulae of optical multilayers [6]. With the formula, layer-by-layer optimization of the thickness for the most effective increase of reflectance can be calculated as the most smooth variation of amplitude reflectance in the complex plane plots [6]. For given optical constants of a pair of materials and a substrate, the optimum thickness structure starts with a specific optimal 1st layer thickness defined by the amplitude reflection coefficients of its boundaries. After the initial a few to several layers appear as an aperiodic structure, the optimum thickness structure varies smoothly into a periodic one as the reflectance increase is saturating at several tens to hundreds layers. Then, the optimum thickness of the top terminating layer departs clearly from the periodic structure since the next material outside is environmental medium, which is vacuum in our case. It should be noted that in the optimum aperiodic structure, the thickness values of the 1st and the last layers appear as specific odd values.

We have used the periodic thicknesses of the pair at the reflectance saturation as the initial set to be used in the next computer optimization routine. The reflection bandwidth with the optimum periodic structure was taken as the start value to be compared since the bandwidth gain by introducing aperiodicity is small enough to be ignored.

In order to optimize layer thicknesses numerically for a desired reflectance profile at a specific wavelength range, a merit function \( MF \) is defined as;

\[
MF = \frac{1}{m} \sum_{k=1}^{m} I_k^2 (R_k - R_{T_k})^2,
\]

where \( m \) is the total number of wavelength sampling with an integer \( k \) representing the position of the sampling equally spaced. At every wavelength \( \lambda_k \), a reflectance difference between the calculated \( R_k \) and the target \( R_{T_k} \) multiplied by the irradiation \( I_k \) to the multilayer structure is calculated to sum up the residuals. In this paper, an unified irradiation was assumed by setting \( I_k=1 \).

For minimization of Eq. (1), we have employed commercially available Simplex, quasi-Newton (Variable) and Gradient methods [5] to treat multiple variables of layer thicknesses. We have found that the result of layer thickness distribution varies depending on the initial layer structure, the leveled target reflectance, the wavelength region, the wavelength sampling interval, and so on. Therefore, the results of the optimum periodic structure described above were used as a common starting structure for comparison. As the target reflectance and the sampling interval, we have tried several values till we obtain reasonably flat spectrum as shown in the following examples. The target wavelength regions for broadening were chosen as preferable values between \( \times1.5 \) and \( \times4.0 \) for practice. The optical constants of materials used for calculation were taken from a web site of the Center for X-ray Optics, Lawrence Berkeley National Laboratory [7].

DESIGN EXAMPLES AT AN EUV REGION

In this example, we tried passband broadening of a Mo/Si multilayer mirror suited for application in the EUV wavelength region. As the initial structure for optimization, a periodic 40 pairs of Mo and Si layer optimized for the maximum peak reflectance at an angle of incidence of 5° was used with their thicknesses set at 2.693 nm and 4.512 nm, respectively. This structure shows the maximum s-reflectance of 70% at a wavelength of 14.0 nm. The target reflectance was set at 35% between a wavelength region of 13.0 nm and 15.0 nm. A wavelength interval of a 0.01 nm was used.

When the iteration numbers for Simplex, quasi-Newton and Gradient methods reached 73587, 113 and 820, the solutions of the thickness distributions were found as shown in Fig. 1 (a), (b) and (c), respectively. From the viewpoint of residual deviations, the Gradient method was the best with 0.740 compared to the Simplex and the quasi-Newton with 2.488 and 1.780, respectively. Note that the iteration in Simplex may include deterioration and the residuals may be increased because of the random nature of the Simplex method [5]. As shown in Fig.1, passband broadening was successfully achieved by all three optimization methods used. Although the thickness structure obtained by Simplex method is of random nature, quasi-Newton and Gradient methods gave more systematic structures. Period thicknesses of each layer indicated by plus marks distribute around the period thickness used for initial structure. The theoretical calculations of the s-reflectance using optimum thickness distributions show good broadened and leveled reflectance profiles as shown in Fig. 1 (d). At the target reflectance of 35%, a
slight reflectance oscillation is still remaining at shorter wavelengths. This oscillation can be made much smaller if we set a smaller target value. Actually, this oscillation was used to judge the optimal condition to set the largest target reflectance for the widest region. In the Gradient case, the optimum layer thickness distribution consists of five layer blocks as shown in Fig. 1 (c). The initial four blocks to 54th layers contribute to the reflection at around 13.5 nm, whereas the fifth final block contributes to around 14.5 nm. This thickness distribution should help avoiding an absorption loss in total by placing the layer blocks for shorter wavelengths at the bottom.

**FIGURE 1.** Thickness distributions of 40 period wideband Mo/Si multilayers optimized by (a) Simplex, (b) quasi-Newton and (c) Gradient methods. An angle of incidence was set at 5 deg. Solid, open and plus marks indicate the layer thickness of odd (Mo), even (Si) layers and period, respectively. The thickness of periodic multilayer used as an initial structure are indicated by dotted lines. (d) Broadened and leveled s-reflectance of Mo/Si multilayers calculated by optimum thickness distributions.

**DESIGN EXAMPLES AT THE WATER WINDOW REGION**

As an example for the passband broadening of multilayers at the water window region, materials of Cr and Sc were selected. We firstly broadened and leveled the reflectance at normal incidence between 3.14 nm and 3.16 nm by Gradient method. The target reflectance was set at 30%. Periodic Cr (0.624 nm)/Sc (0.953 nm) composed of 500 period was used as the initial structure. Then, using the result of this optimum thickness distribution as the initial structure, 15% broadband Cr/Sc multilayer was derived at a wavelength region between 3.13 nm and 3.17 nm by the same optimization methods.

**FIGURE 2.** (a) Thickness distribution for a target reflectance of 30% optimized by Gradient method. Solid and dotted lines indicate the layer thickness of odd (Cr) and even (Sc) layers of the periodic multilayer, respectively. Solid, open and plus marks indicate the layer thickness of odd, even layers and period, respectively. (b) Broadened and leveled reflectance at normal incidence of Cr/Sc multilayers calculated by optimum thickness distributions.
The optimum thickness distribution having a leveled wideband reflectance of 30% is shown in Fig. 2 (a). Odd and even layers show thickness variations with the period being almost constant except for a few periods. Since the most of odd layer thickness is larger than that of periodic multilayer, the optimum thickness distribution would be within a technical limit to realize. As shown in Fig. 2 (b), the theoretical reflectance spectra for the design targets of 30% as well as a case of 15% proved wide enough profiles. Compared with the resolution $\lambda/\Delta\lambda = 286$ of the periodic multilayer, bandwidth broadening factors of these designs are $286/137=2.09$ and $286/66=4.3$, respectively.

**FABRICATION OF BROADENED AND LEVELD MO/SI MULTILAYER MIRRORS**

To test the experimental feasibility, the wideband Mo/Si multilayers designed by the Simplex and the Gradient methods for the target reflectance of 35% between 13.0 nm and 15.0 nm were fabricated by our ion beam sputtering (IBS) system [8]. The deposition durations of each layer were controlled to the optimum thickness structures derived. The designed thickness of null is treated by adding the layer thicknesses on both sides into a thick equivalent layer since the materials of the layers are the same. This treatment is correct theoretically though the total effective number of layers is reduced by two.

EUV reflectance of the wideband Mo/Si multilayer mirrors fabricated were measured at BL-12A, Photon Factory, KEK with a reflectometer. As shown in Fig. 3, s-reflectance more than 15% between 13.0 nm and 15.0 nm was successfully achieved. The reduction of the reflectance level could be attributed to the thickness controlling error during fabrication. Optimization methods with conventional algorithms were found to be effective to search for aperiodic EUV multilayers of a broadened and leveled reflectance. The use of passband broadened multilayer mirrors should help relieving the severe engineering tolerances of the wavelength matching for relaying reflecting optics including imaging optics.

**FIGURE 3.** The measured s-reflectance of two broadened and leveled Mo/Si multilayer mirrors.

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