09

# Reflection of restricted beams of extreme ultraviolet radiation from multilayer mirrors

© V.I. Punegov, D.M. Malkov

Institute of Physics and Mathematics, Federal Research Center „Komi Scientific Center, the Ural Branch of the Russian Academy of Sciences“, Syktyvkar, Russia
E-mail: vpunegov@dm.komisc.ru

*Received May 23, 2023*
*Revised October 4, 2023*
*Accepted October 9, 2023*

The influence of the beam size on the reflection of extreme ultraviolet radiation from a multilayer mirror is investigated on the basis of two-dimensional diffraction equations for slowly varying amplitudes. The boundary conditions of the diffraction problem are considered in the case of geometric optics and the Fresnel approximation. The results of numerical simulation of reciprocal space maps, as well as their sections in the horizontal (non-specular) qx and vertical (specular) qz directions are shown.

**Keywords:** multilayer mirror, spatially restricted beams, extreme ultraviolet radiation, geometric optics, Fresnel approximation.

DOI: 10.61011/0000000000

Multilayer mirrors for reflecting extreme ultraviolet (EUV) radiation are used in EUV–thography [1] and in astronomy [2]. When calculating the reflection of soft EUV-radiation from multilayer mirrors, one-dimensional diffraction equations for slowly varying amplitudes, recurrent relations and a matrix approach are used. The comparison of the results obtained using the above methods is presented in [3]. All these methods are related to one-dimensional soft X-ray diffraction and assume that the incident radiation is a plane wave, which is unrestricted in space. However, in experimental measurements, the incident beam is always restricted by the presence of slits and collimators. The influence of the transverse size of the incident beam on the reflection coefficient of EUV-radiation from multilayer mirrors has not been studied. Using the formalism of X-ray diffraction of spatially restricted beams [4] the angular distribution of the reflected intensity of EUV-radiation from a multilayer mirror was studied. In contrast to [4], in this paper, the boundary functions are considered in the Fresnel approximation.

To describe the dynamical diffraction of a spatially restricted EUV-beam from a multi-layer mirror, a rectangular coordinate system was introduced. In it the $x$ and $y$ axes of which are parallel to the input surface, and the $z$ axis is directed into the depth of the mirror and $x0z$ is the diffraction plane. The scheme of reflection of a restricted beam of EUV-radiation from a multilayer mirror is shown in Fig.1. The size of the incident beam is restricted by a slit $S_1$ of width $w_1$. Before it hits the detector the reflected wave is limited by a slit $S_2$ of width $w_2$. The distance from the entrance slit to the multilayer mirror is equal to $L_{S1}$. The slit $S_2$ is located at a distance $L_{S2}$ to the position-sensitive detector or the analyzer–detector system.

To study the reflection of EUV-radiation from a multilayer mirror, two-dimensional equations of dynamical X-ray scattering were used [5,6]. Applying the formalism of diffraction of spatially limited beams [4] , the system of two-dimensional equations is transformed into one-dimensional equations that have an analytical solution in Fourier space. The amplitude of the reflected wave of EUV-radiation $E_1(q_x, q_z)$ has the form

$$E_1(q_x, q_z) = \frac{a_1 f}{2\pi} \int\limits_{-\infty}^{+\infty} d\kappa \frac{\exp(i\xi l_z) - 1}{Q} Y_{in}(\kappa) Y_{ex}(\kappa - q_x), \tag{1}$$

where $\xi = \sqrt{\psi^2 - 4f^2 a_1^2}$, $\psi = 2a_0 - (2\kappa - q_x)\cot\theta_B - q_z$ is the angular parameter, $f$ — which reduces the reflection coefficient of EUV radiation from multilayer mirror-due to

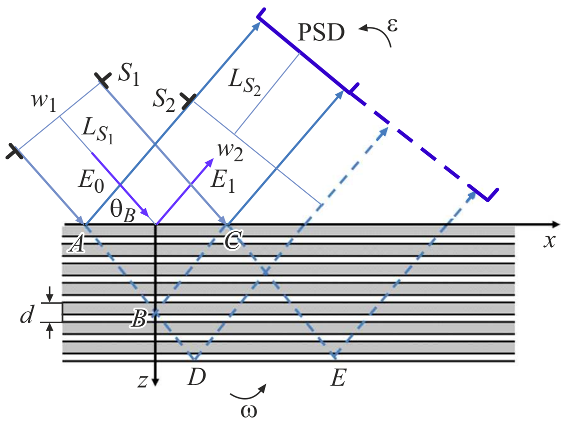


**Figure 1.** Schematic representation of the reflection of a spatially restricted EUV-wave from a multilayer mirror with a period $d$. $E_0$ and $E_1$ are the amplitudes of the incident and reflected beams. PSD is position sensitive detector.

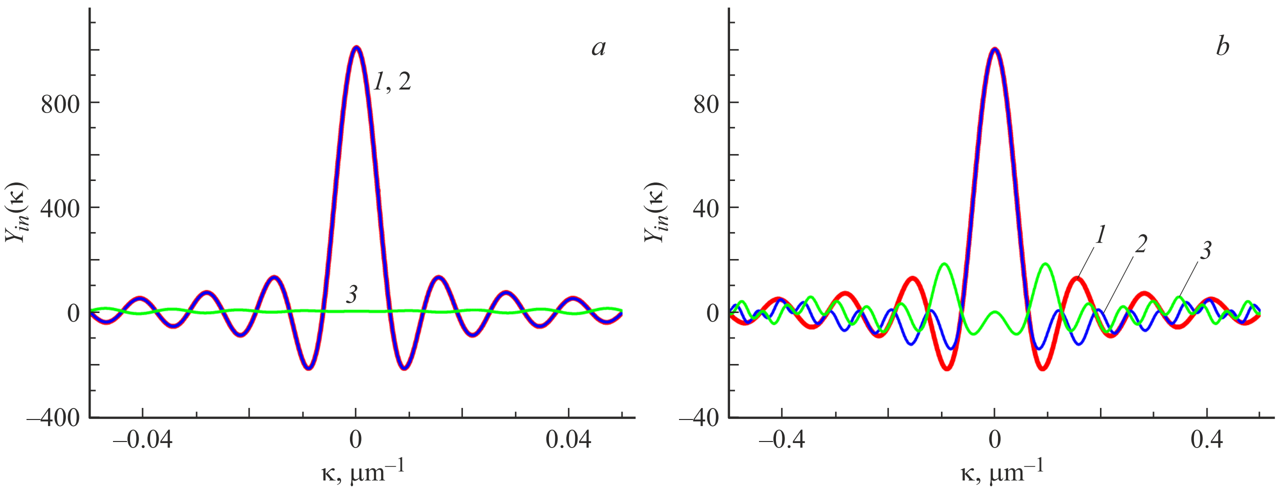


**Figure 2.** Boundary functions in Fourier space for incident EUV-radiation with a wavelength of 12.93 nm. Beam width $w_1 = 1000\,\mu$m (*a*) and $100\,\mu$m (*b*). The distance from the slit to the multilayer mirror $L_{S1} = 100$ mm. Curve *1* corresponds to the geometrical optics approximation, curves *2* and *3* refer to the Fresnel approximation for the real and imaginary parts$Y_{in}(\kappa)$, respectively.

defects in the multilayer structure, $l_z$ is the thickness of the multilayer mirror In solution (1), the rest of the parameters are written as $Q = \xi_1 \exp(i\xi l_z) - \xi_2$, $\xi_{1,2} = (-\psi \pm \xi)/2$, $a_0 = \pi\chi_0/(\lambda \sin\theta_B)$, $a_1 = C\pi\chi_1/(\lambda \sin\theta_B)$, where $\lambda$ is the wavelength of EUV-radiation in vacuum, $C$ is the polarization factor ($C = 1$ for $\sigma$-polarization and $C = \cos 2\theta_B$ for $\pi$-polarization), $\theta_B$ is the Bragg angle for a multilayer mirror with thickness $d_{t,b}$ of alternating layers in the mirror period $d = d_t + d_b$. The reflection coefficient of EUV-radiation from the multilayer mirror depends on the Fourier coefficients of polarizability in the direction of transmission and diffraction

$$\chi_0 = \frac{\chi_t d_t + \chi_b d_b}{d}$$

$$\chi_1 = \frac{\chi_t - \chi_b}{\pi} \sin\left(\pi \frac{d_t}{d}\right),$$

where $\chi_{t,b}$ is Fourier-coefficients of polarizability of the upper ($t$) and lower ($b$) layers of the period multilayer structure.

In the case of a triple-axis diffraction scheme, the reflection intensity depends on the an-gular position of the sample $\omega$ and the detector (analyzer)$\varepsilon$. They are related to the projections $q_x$ and $q_z$ of the vector $\mathbf{q} = \mathbf{Q} - (2\pi/d)\mathbf{n}$ by relations $q_x = (2\pi/\lambda)\sin\theta_B(2\omega - \varepsilon)$, $q_z = -(2\pi/\lambda)\cos\theta_B\varepsilon$, where $\mathbf{Q} = \mathbf{k}_1 - \mathbf{k}_0$ is the diffraction vector, $\mathbf{n}$ is the normal to the surface of the multilayer mirror, $\mathbf{k}_{0,1}$ are the wave vectors of the incident and reflected X-ray waves. Solution (1) contains the boundary functions of the incident $Y_{in}(\kappa)$ and reflected $Y_{ex}(\kappa - q_x)$ EUV-beams in the Fourier space.

Slit-limited propagation of an electromagnetic wave is commonly distinguished at different distances from the slit. At short distances (near zone), geometric optics is valid. At large distances from the slit (far zone) there is a Fraunhofer diffraction field. In the transition region between geometrical optics and the Fraunhofer zone, Fresnel diffraction is considered. Since there are no clearly defined boundaries between these zones, it is customary to speak of diffraction in the approximation of a specific region, the size of which depends on the wavelength of the electromagnetic radiation, the size of the slit and the distance from it.

In the geometrical optics approximation, we do not take into account distortions of the EUV-radiation wavefront as it passes through the slit. For the boundary function of the incident beam in the case of geometric optics, we obtain

$$Y_{in}(\kappa) = Y_{in}^0(\kappa) = \frac{\sin[\kappa w_1/(2\sin\theta_B)]}{\kappa/2}.$$

In the Fresnel approximation, this function has the form

$$Y_{in}(\kappa) = P(\kappa, L_{S1})Y_{in}^0(\kappa),$$

where

$$P(\kappa, L_{S1}) = \exp\left(-i\lambda \frac{L_{S1}\kappa^2}{4\pi[\sin\theta_B]^2}\right)$$

is the propagator in the Fourier space [7].

The transmittance of the reflected wave by the slit $S_2$ in the Fourier space is equal to

$$Y_{ex}(\kappa - q_x) = Y_{ex}^0(\kappa - q_x) = \frac{\sin[(\kappa - q_x)w_1/(2\sin\theta_B)]}{(\kappa - q_x)/2}$$

in the case of geometric optics and

$$Y_{ex}(\kappa - q_x) = P(\kappa - q_x, L_{S2})Y_{ex}^0(\kappa - q_x)$$

in the Fresnel approximation, where

$$P(\kappa - q_x, L_{S2}) = \exp\left(-i\lambda \frac{L_{S2}[\kappa - q_x]^2}{4\pi[\sin\theta_B]^2}\right).$$

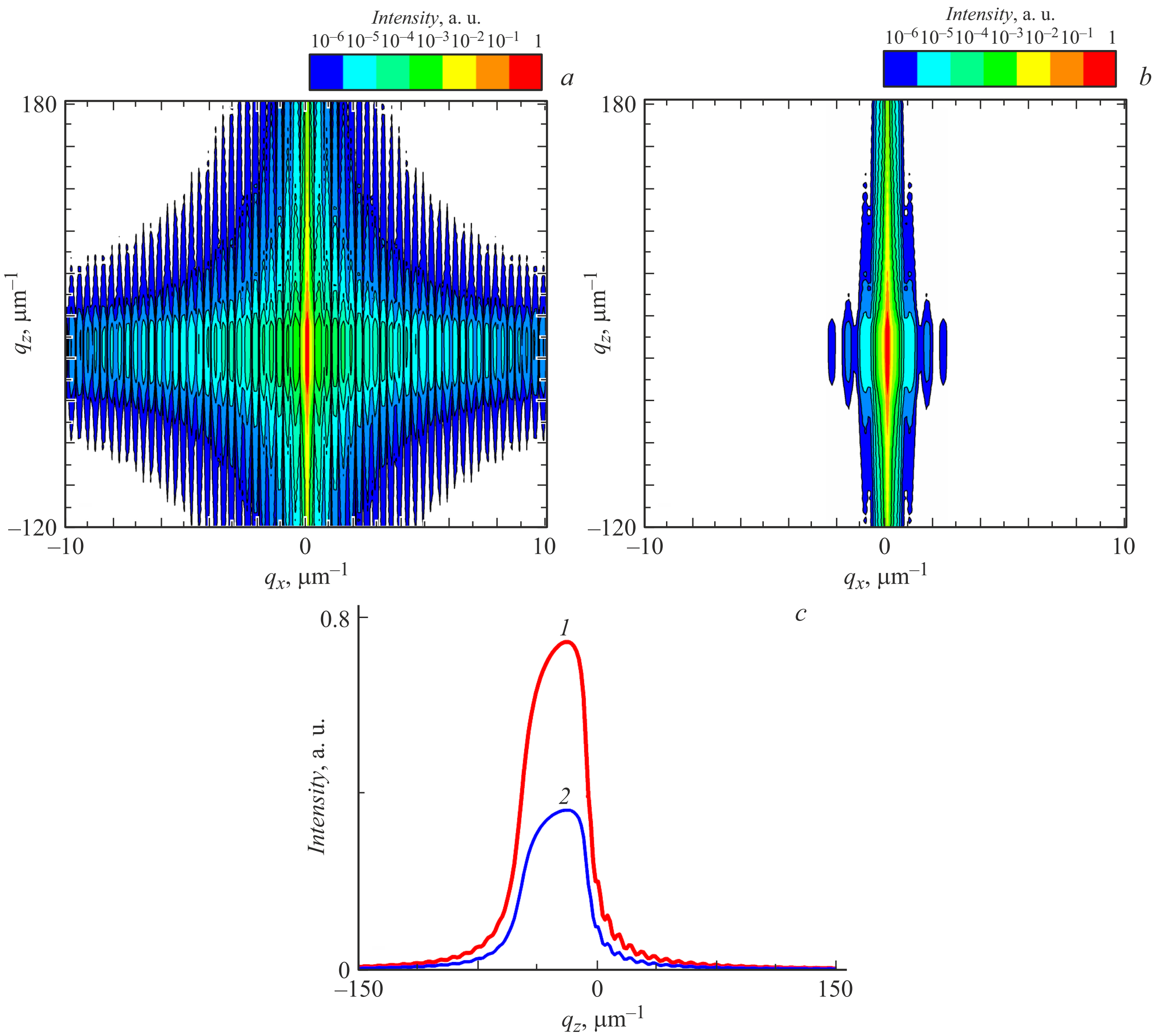


**Figure 3.** Calculated RSMs from Mo/Si multilayer mirror with boundary functions in the case of geometric optics (*a*) and Fresnel approximation (*b*). *c* — calculated $q_z$-cross sections of RSMs from Mo/Si multilayer mirror with boundary functions in the case of geometric optics (*1*) and Fresnel approximation (*2*).

Figure 2 shows boundary functions in Fourier space for large and relatively small sizes of the spatially restricted wave front of the EUV-radiation. In the case of a large width of the incident beam, the boundary functions for geometric optics and the Fresnel approximation coincide (Fig. 2, *a*). For a $100\,\mu$m beam, there are noticeable differences (Fig. 2, *b*).

Numerical calculations of the reflection of spatially restricted beams from a Mo/Si multilayer mirror for EUV-radiation with a wavelength of 12.93 nm are performed based on solution (1). The multilayer Mo/Si structure had a period of 6.9 nm with a molybdenum content of 38.7% and silicon of 61.3%. The number of periods is 110, which corresponds to the thickness of the multilayer mirror $l_z = 0.76\,\mu$m. The Fourier coefficients of polarizability of molybdenum $\chi_{\mathrm{Mo}} = -0.138 + i0.0125$ and silicon were used in calculations $\chi_{\mathrm{Si}} = -0.00324 + i0.00308$.

Such a structure is ideally optimized for maximum reflection coefficient [1]. The length of the primary Bragg extinction is $0.095\,\mu$m. The Bragg angle is $69.55°$. X-ray maps of the angular distribution of the scattering intensity in reciprocal space (reciprocal space maps, RSM) [8] and their cross sections are calculated using solution (1).

Figure 3 shows the calculated RSMs of a Mo/Si multilayer mirror with boundary functions in the case of geometric optics (*a*) and the Fresnel approximation (*b*). The following parameters of the diffraction scheme were used in the calculations: the size of the incident and reflected beam of EUV-radiation is $100\,\mu$m,; the distance from the entrance slit $S_1$ to the surface of the multilayer mirror and from the exit slit $S_2$ to the position sensitive detector is 100 mm. The $S_2$ slit is located in the near field of the reflected beam (of the order of 20 mm from the multilayer structure), and geometrical optics is valid. Therefore, interference distortions in the structure of the diffracted wave from due to the spatial confinement of the EUV of -radiation to the $S_2$ slit are not considered. From, due to the shallow depth of the primary Bragg extinction, the main contribution to the reflected intensity comes from the region with the triangle cross-section *ABC* of the multilayer structure. If there is no slit $S_2$, the detector receives the entire diffraction intensity from the section with a parallelogram cross section *ADEC*. However, the contribution to the reflection coefficient during diffraction of the EUV-radiation in the region with the cross-section of the *BDEC* figure is significantly small (Fig. 1). Increasing the slit size $S_2$ does not affect the $q_z$-profile of the RSM map cross section from Mo/Si multilayer mirror, but it does change the appearance of the angular distribution of the reflectance intensity in the reciprocal space, which becomes asymmetric [9]. Calculations show that RSMs with boundary functions in the case of geometric optics and the Fresnel approximation differ significantly (Fig. 3, $a, b$). The $q_z$-cross sections of the RSMs are also different (Fig. 3, $c$).

It should be noted that in the case of geometric optics, the $q_z$-cross-sections of RSMs of spatially restricted EUV-radiation completely coincide with the reflection profile of a plane wave, independently of the beam size. In the Fresnel approximation for wide beams, the calculated reflection coefficients were found to be equal with the reflection coefficients for a plane wave. For beams of relatively small sizes in the Fresnel approximation, a decrease in the calculated reflection coefficients were observed (Fig. 3, $c$).

At present, soft X-ray diffuse scattering angular distribution maps in reciprocal space [10] are used to analyze defects in multilayer structure. However, the angular distribution of the total scattering intensity is affected by the specular component, which can be taken into account using the approach presented.

### Funding

This study was supported by grant No. 23-22-00062 from the Russian Science Foundation, (https://rscf.ru/project/23-22-00062/).

### Conflict of interest

The authors declare that they have no conflict of interest.

## References

[1] N.I. Chkhalo, S.A. Gusev, A.N. Nechay, D.E. Pariev, V.N. Polkovnikov, N.N. Salashchenko, F. Schäfers, M.G. Sertsu, A. Sokolov, M.V. Svechnikov, D.A. Tatarsky, Opt. Lett., **42**, 5070 (2017). DOI: 10.1364/OL.42.005070

[2] S.A. Bogachev, N.I. Chkhalo, S.V. Kuzin, D.E. Pariev, V.N. Polkovnikov, N.N. Salashchenko, S.V. Shestov, S.Yu. Zuev, Appl. Opt., **55**, 2126 (2016). DOI: 10.1364/AO.99.099999

[3] I.V. Kozhevnikov, A.V. Vinogradov, J. Russ. Laser Res., **16**, 343 (1995). DOI: 10.1007/BF02581074.

[4] V.I. Punegov, S.I. Kolosov, K.M. Pavlov, J. Appl. Cryst., **49**, 1190 (2016). DOI: 10.1107/S1600576716008396

[5] S. Takagi, Acta Cryst., **15**, 1311 (1962). DOI: 10.1107/S0365110X62003473

[6] D. Taupin, Bull. Soc. Franc. Mineral. Crist., **87**, 469 (1964).

[7] V.G. Kohn, I. Snigireva, A. Snigirev, Phys. Status Solidi B, **222**, 407 (2000). DOI: 10.1002/1521-3951(200011)222:2<407::AID-PSSB407>3.0.CO;2-X

[8] V.I. Punegov, Phys. Usp., **58**, 419 (2015). DOI: 10.3367/UFNr.0185.201505a.0449.

[9] V.I. Punegov, K.M. Pavlov, A.V. Karpov, N.N. Faleev, J. Appl. Cryst., **50**, 1256 (2017). DOI: 10.1107/S1600576717010123

[10] A. Haase, V. Soltwisch, S. Braun, C. Laubis, F. Scholze, Opt. Express, **25**, 15441 (2017). DOI: 10.1364/OE.25.015441

*Translated by Ego Translating*