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Dispersion elements for X-ray mirror spectrometer on a range of 7−30 nm

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Multilayer interference structures acting as dispersion elements for a mirror spectrometer for a wavelength range of 7−30 nm have been calculated and synthesized. Three elements are implemented: for the range $\lambda = 7-12$ nm — multilayer structure Mo/B_4C (number of periods $N = 60$, period thickness $d = 6.5$ nm); for the range $\lambda = 11-18$ nm — Mo/Be ($N = 50$; $d = 9.83$ nm) and for the range $\lambda = 17-30$ nm —Be/Si/Al ($N = 40$; $d = 18.2$ nm). For the entire spectral range, an efficiency of more than 10% was obtained at a wavelength resolution of 0.15−1.0 nm.

Keywords: SXR and EUV radiation, multilayer X-ray mirrors, laser plasma, spectroscopy.

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Introduction

The so-called „betatron radiation“ is the simplest synchrotron radiation setup relying on the principles of laser acceleration of electrons. Laser-plasma betatron radiation is generated in the process of electron acceleration in a wake produced in plasma by a femtosecond laser pulse. A transverse force inducing electron oscillations about the wake axis acts on accelerated electrons in the wake. The characteristics of radiation need to be examined in a wide wavelength range to study the physics of interaction between laser radiation and matter and obtain and systematize data on the spectral composition, emission efficiency, monochromaticity, and spatial coherence of radiation of an X-ray source as functions of the laser pulse parameters and the laser target type. Data on the absolute intensity of radiation are just as important as its spectral characteristics. A spectrometer [1] based on multilayer X-ray mirrors and an SPD-100UV silicon photodiode [2], which served as an absolute calibrated detector of soft X-ray (SXR) and extreme ultraviolet (EUV) radiation, was constructed to address these challenges. A wavelength range of 7−30 nm, where experimental data on synthesis of high-reflection multilayer X-ray mirrors (MXRMs) are available, was chosen as the operating one.

1. Calibration of X-ray optical elements

The task is specific in that both high reflection coefficients and a fine spectral resolution need to be achieved. Thus, in order to measure efficiently the radiation spectrum of a betatron source, one should use such an element expanding radiation into a spectrum that has a fine spectral resolution (ratio $\lambda/\delta\lambda$) and a high reflection coefficient. The discussed spectrometer was designed to have a spectral resolution better than 1 nm within the entire wavelength range indicated above. The design of multilayer mirrors potentially applicable as dispersion elements within the 7−30 nm spectral range was calculated and optimized. A number of materials with low absorption in the indicated wavelength range were analyzed for this purpose. The refraction index in the X-ray wavelength range is close to, but somewhat lower than unity. Thus, it is convenient to use the following general form of refraction index (n):

$$n = 1 - \delta + i\gamma, \tag{1}$$

where δ is the real part of the refraction index correction and γ is its imaginary part. Figure 1 shows the curves of real and imaginary parts of the refraction index correction for the most promising materials in the considered wavelength range.

A material pair with the greatest jump of the real refraction index part (the so-called „absorber“ (heavy material) and „spacer“ (light material)) normally offers the most promise for synthesis of a multilayer interference structure. It follows from Fig. 1, *a* that Mo has the highest δ value within the wavelength range indicated above. However, its absorption increases dramatically at wavelengths exceeding 15 nm (Fig. 1, *b*), thus making it a poor choice of a base material for a multilayer structure operating at wavelengths greater than 17 nm. At the same time, Al does, in contrast, have an absorption edge in the vicinity of 17 nm, and the imaginary part of its refraction index decreases abruptly by more than an order of magnitude and assumes a value lower than the ones corresponding to all the other candidates in Fig. 1. Therefore, these two materials are obviously preferable for application as components of a

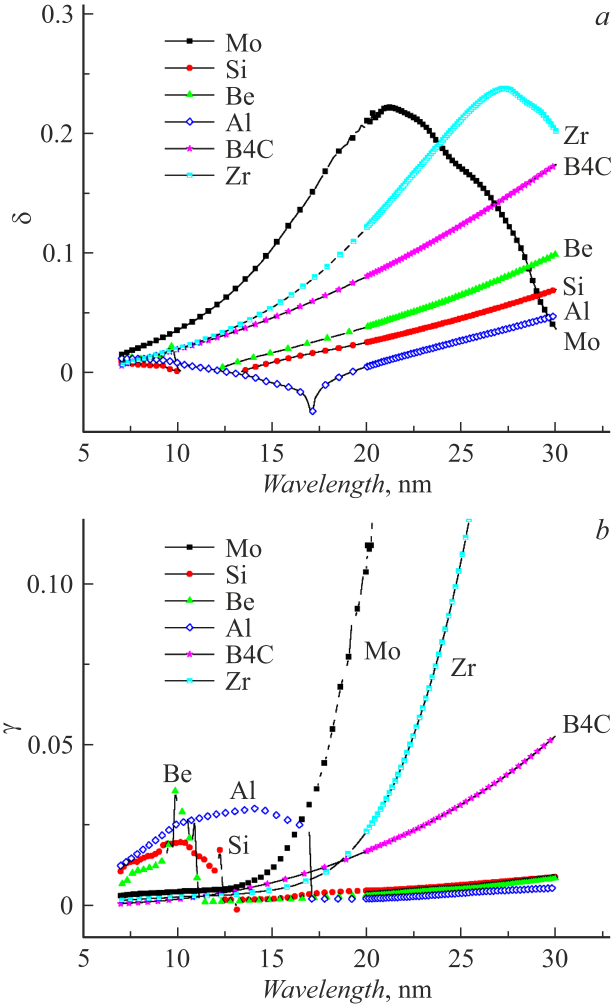

Figure 1. Real (a) and imaginary (b) parts of refractive indices of several materials [3].

multilayer structure in the considered wavelength range. Different combinations of reflective materials and spacers were simulated using the Multifitting code [4]. The number of periods in a structure and the ratio of material thicknesses in a period were modeled; the real substrate roughness and other parameters were taken into account. The influence of the absorber fraction in a period on reflective and spectral characteristics of a mirror is characterized in Fig. 2 and Table 1. Calculations were performed for grazing angle $\varphi = 72.3°$ (here and elsewhere, angles are measured from the surface).

It can be seen that the ratio of materials in a structure ($\beta = d_{ab}/d$, where d_{ab} is the absorber layer thickness in a structure period and d the thickness of a period) exerts a considerable influence on the peak reflection coefficient and the spectral width ($\delta\lambda$) of the Bragg maximum. Thus, the structure parameters were optimized to calculate the spectrometer MXRM characteristics. Three mirror elements were needed to cover the above-indicated spectral range with a required spectral resolution. Their structure and parameters are presented in Table 2, where β is the fraction of a high-absorption material (absorber) in a period, N is the number of periods, $\Delta\lambda$ is the wavelength range, $\Delta\varphi$ is the corresponding range of mirror rotation angles, and $\delta\lambda$ is the half-width of the Bragg maximum at half height.

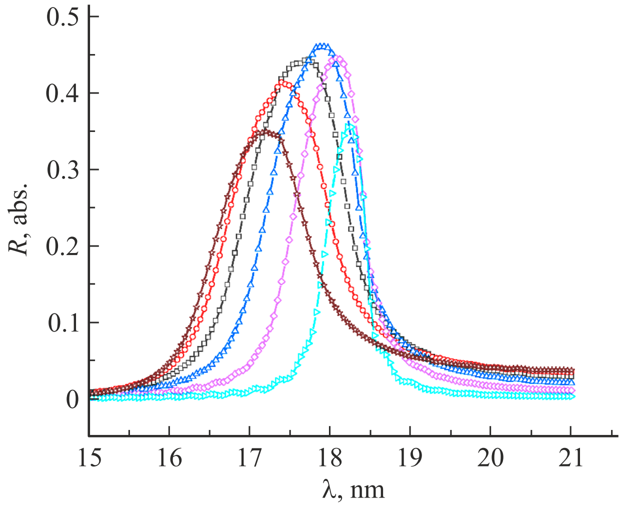

Figure 2. Calculated curves of the spectral dependence of reflection of X-ray radiation from a Mo/Be mirror ($d = 10$ nm, number of periods $N = 50$, $\varphi = 72.3°$).

Table 1. Parameters of a Mo/Be MXRM at various ratios β

β	R, %	$\delta\lambda$, nm
0.1	35.6	0.6
0.2	44.4	0.92
0.3	45.9	1.2
0.4	44.3	1.35
0.5	41.2	1.4
0.6	34.8	1.35

Table 2. MXRM parameters

Structure	d, nm	β	N	$\Delta\lambda$, nm	$\Delta\varphi$, °	$\Delta\lambda$, nm
Mo/B4C	6.5	0.4	100	7–12	24–52	< 0.5
Mo/Be	10.0	0.24	50	12–18	38–72	< 1.0
Al/Be	14.0	0.4	100	18–30	31–67	< 1.0

Curves of mirror reflection of unpolarized radiation for the modeled structures at different wavelengths and the corresponding incidence/reflection angles, which fall into the interval that is mechanically accessible for scanning by the spectrometer, are shown in Fig. 3.

It is evident that the proposed material pairs should provide high (more than 10%) reflection coefficients with a required spectral resolution within the entire operating wavelength range of the spectrometer.

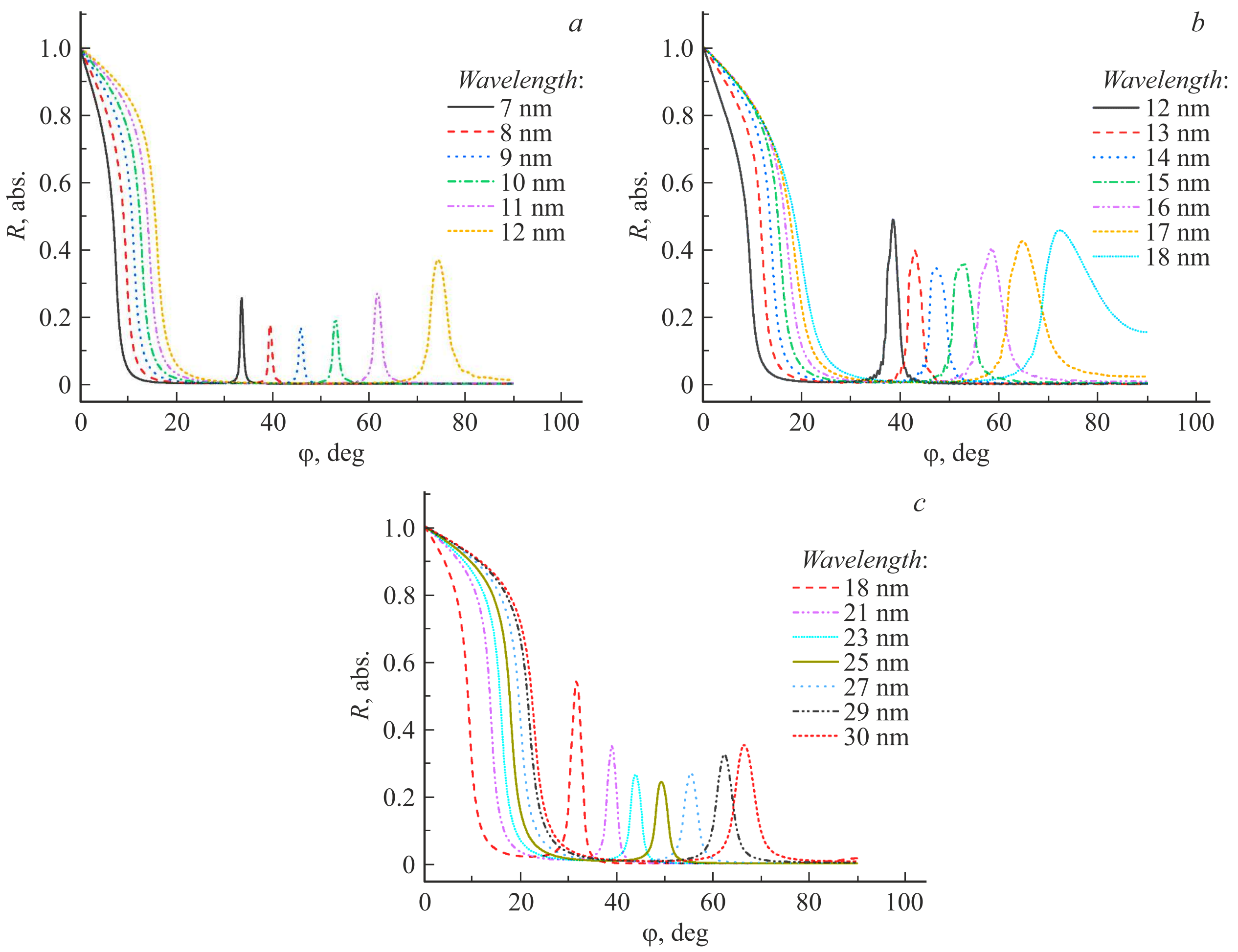

Figure 3. Calculated curves of the angular dependences of reflection of X-ray radiation from spectrometer mirrors: *a* — Mo/B4C ($d = 6.5\,\mathrm{nm}$, $N = 60$) for the 7–12 nm wavelength range; *b* — Mo/Be ($d = 10.0\,\mathrm{nm}$, $N = 50$) for the 12–18 nm wavelength range; *c* — Al/Be ($d = 14.0\,\mathrm{nm}$, $N = 100$) for the 18–30 nm wavelength range.

2. Spectrometer mirrors

Multilayer structures were synthesized based on the obtained calculated data by magnetron sputtering using a fabrication system characterized in [5]. Film coatings were deposited onto standard super-polished silicon substrates [6] in Ar atmosphere under a working pressure of $\sim 1 \cdot 10^{-3}$ Torr. The following three structures were synthesized this way:

1. Mo/B4C mirror (for the $\Delta\lambda = 7{-}12\,\mathrm{nm}$ wavelength range) with period $d = 6.5\,\mathrm{nm}$.
2. Mo/Be mirror ($\Delta\lambda = 11{-}18\,\mathrm{nm}$) with period $d = 9.8\,\mathrm{nm}$.
3. Be/Si/Al mirror ($\Delta\lambda = 17{-}30\,\mathrm{nm}$) with period $d = 18.2\,\mathrm{nm}$.

The Be/Al structure period was modified by an additional Si layer acting as an antidiffusion (barrier) layer. It has been demonstrated in [7] that the introduction of such a layer provides an opportunity to reduce the transition region width and, consequently, improve the reflective characteristics of a mirror.

The reflective properties of an MXRM (peak reflection coefficient and spectral width of the Bragg maximum) need

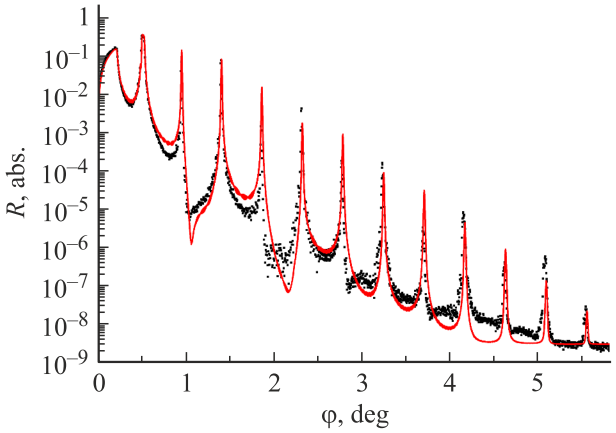

Figure 4. Experimental and theoretical dependences of mirror reflection of X-ray radiation with energy $E = 12\,\mathrm{keV}$ on the grazing angle for the Mo/B4C MXRM. Dots represent measurement data, and the solid curve is the result of simulation in Multifitting.

Table 3. Structural parameters of spectrometer MXRMs

Structures	Number of periods	Thickness of a period, nm	Layer thickness, nm	Transition region width, nm
Mo/B4C	70	6.50	B4C−3.9	σ(Mo-on-B4C)−0.46
			Mo−2.6	σ(B4C-on-Mo)−0.29
Mo/Be	50	9.84	Be−7.5	σ(Mo-on-Be)−0.7
			Mo−2.34	σ(Be-on-Mo)−0.29
Be/Si/Al	40	18.2	Al−9.80	σ(Be-on-Al)−0.80
			Si−1.0	σ(Al-on-Si)−0.60
			Be−7.40	σ(Si-on-Be)−0.80

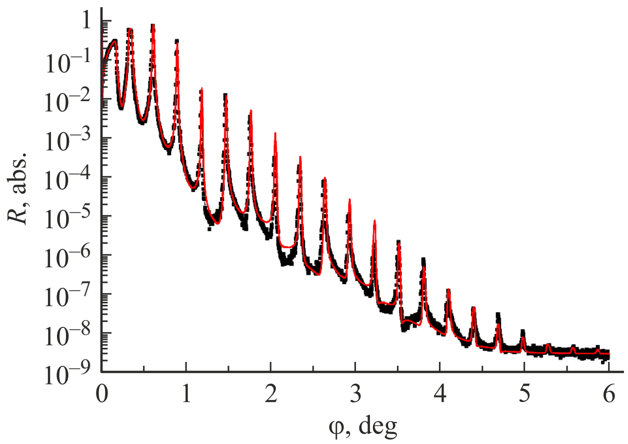

Figure 5. Experimental and theoretical dependences of mirror reflection of X-ray radiation with energy $E = 12\,\text{keV}$ on the grazing angle for the Mo/Be MXRM. Dots represent measurement data, and the solid curve is the result of simulation in Multifitting.

to be determined at each wavelength within the spectral range in order to reconstruct the spectral characteristics of an X-ray radiation source. All MXRMs were studied at the Kurchatov Synchrotron Radiation Source („FAZA“ station) to obtain the needed data. Structural parameters of mirrors were reconstructed based on the results of small-angle X-ray reflectometry (quanta energy $E = 12\,\text{keV}$), and their spectral characteristics in the operating wavelength range were calculated by fitting the reflection curves in Multifitting [4]. Figures 4−6 present the angular dependences of reflection of X-ray radiation with an energy of 12 keV from Mo/B4C, Mo/Be, and Be/Si/Al structures, respectively.

The structural parameters of multilayer X-ray mirrors were determined in Multifitting based on the reflectometry data at a radiation energy of 12 keV (Table 3).

Thus, the structural parameters of all dispersion elements corresponding to the above-indicated wavelength subbands were determined. A calibration curve (dependence of the reflected wavelength on the radiation incidence angle) was calculated for each mirror in Multifitting and verified at several wavelengths within the operating range using a laboratory X-ray reflectometer based on the X-ray spectrometer of an RSM-500 monochromator [8]. Example angular dependences of the reflection coefficient for three mirrors used in the spectrometer at the operating wavelengths in the SXR and EUV ranges are presented in Fig. 7.

Calibration curves and spectral dependences of the resolution of the instrument (half-width of the Bragg maximum at half height) and the peak reflection coefficient for all three structures are shown in Figs. 8−10.

It can be seen that the spectral transmission band of multilayer structures remains no greater than $\delta\lambda = 1\,\text{nm}$ within the entire operating wavelength range of the spectrometer ($\lambda = 6.6{-}30\,\text{nm}$). Since the K-absorption edge of

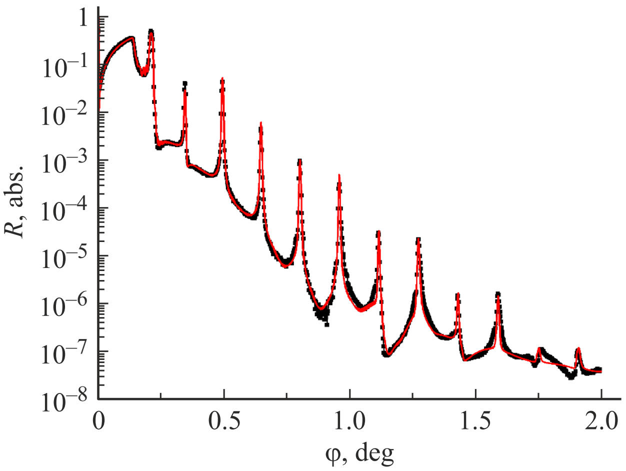

Figure 6. Experimental and theoretical dependences of mirror reflection of X-ray radiation with energy $E = 12\,\text{keV}$ on the grazing angle for the Be/Si/Al MXRM. Dots represent measurement data, and the solid curve is the result of simulation in Multifitting.

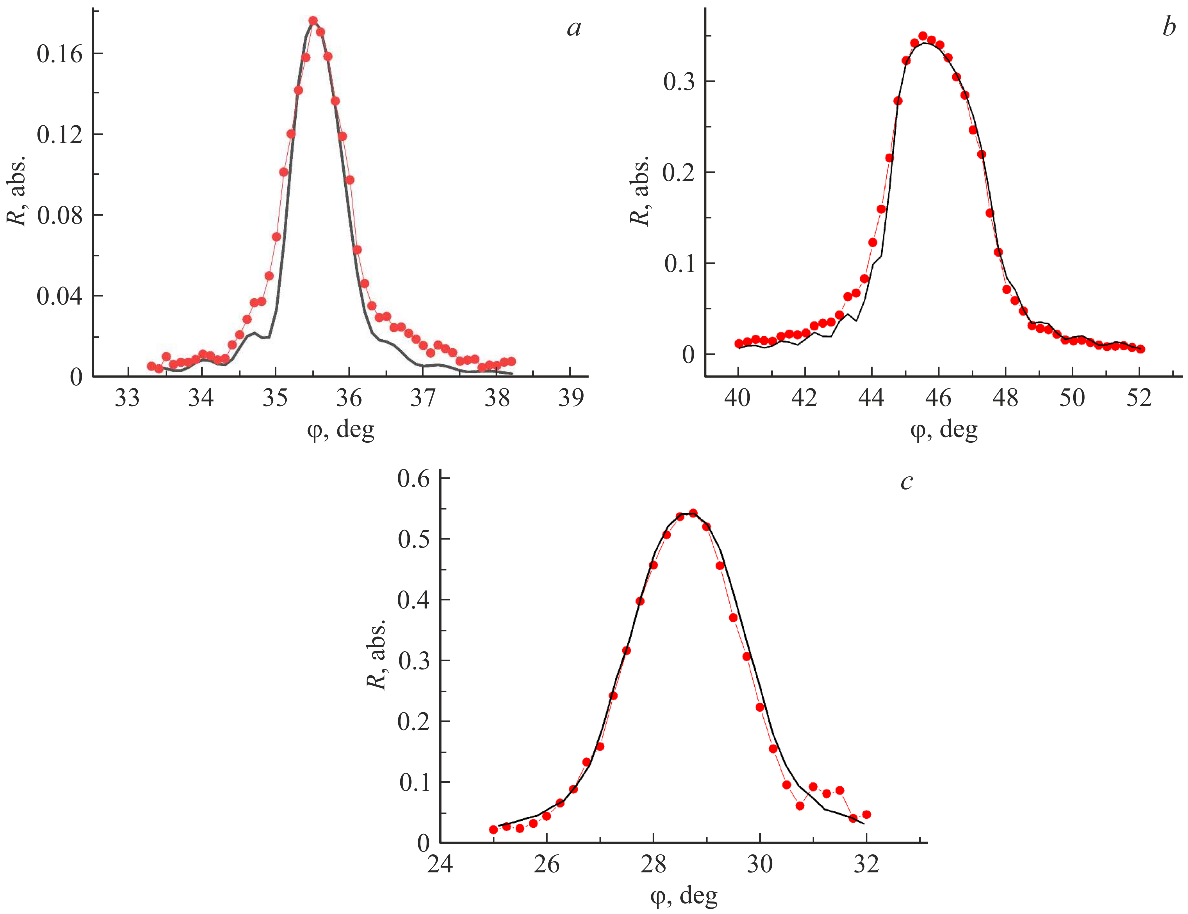

Figure 7. Angular dependences of the MXRM reflection coefficient: *a* — Mo/B4C, wavelength $\lambda = 7.22$ nm; *b* — Mo/Be, $\lambda = 9.34$ nm; *c* — Be/Si/Al, $\lambda = 11.4$ nm. Dots represent measurement data, and the solid curve is the result of simulation in Multifitting.

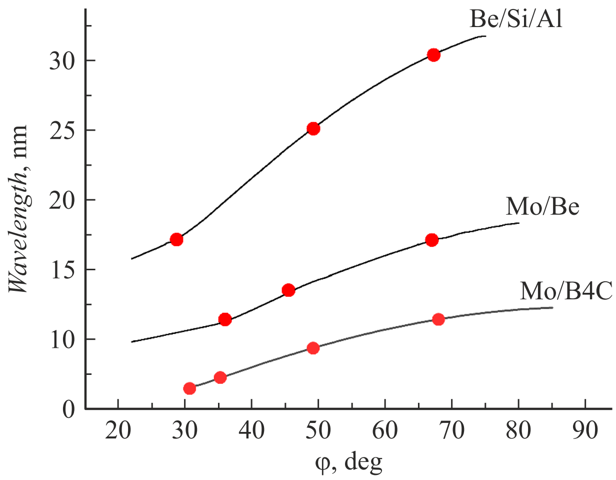

Figure 8. Calibration curves for Mo/B4C, Mo/Be, and Be/Si/Al mirrors.

boron makes it impossible for a Mo/B4C mirror to be an efficient reflector at wavelengths shorter than $\lambda = 6.6$ nm, measurements in this subband are feasible only at radiation incidence angles no smaller than 30°. However, the spectrometer may still be used efficiently for diagnostics of the spectral composition of SXR and EUV radiation sources within the rest of the spectral range, which corresponds to

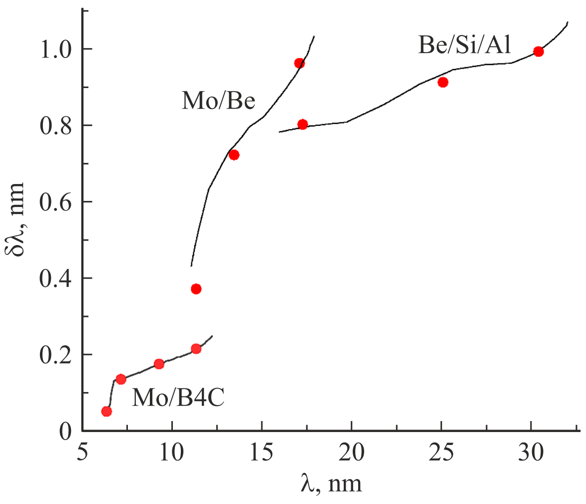

Figure 9. Wavelength dependence of the spectral resolution of mirrors. Dots represent measurement data, and the solid curve is the result of simulation in Multifitting.

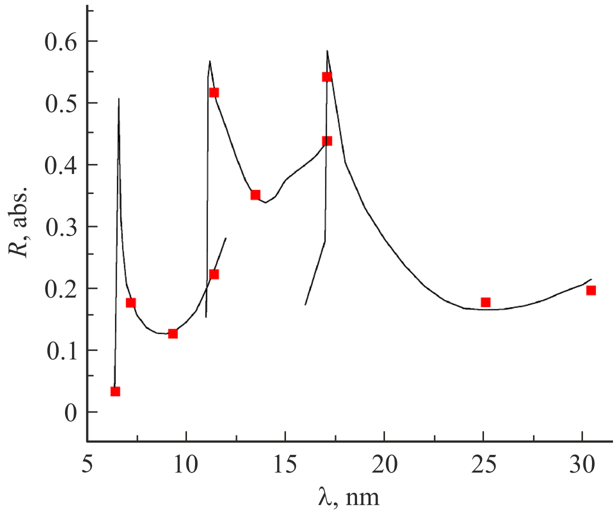

Figure 10. Wavelength dependence of the peak reflection coefficient of mirrors. Dots represent measurement data, and the solid curve is the result of simulation in Multifitting.

incidence angles of 30°$-$75° (for the Mo/B4C MXRM) or 20°$-$75° (for the other two mirrors) and wavelengths of $\lambda = 6.6-30$ nm.

Conclusion

Multilayer X-ray mirrors optimized for spectroscopy studies within the 7$-$30 nm wavelength range were synthesized and tested. High (more than 10%) reflection coefficients were obtained at a required spectral resolution ($\delta\lambda \leq 1$ nm) within the entire operating wavelength range of the spectrometer.

This wavelength range was divided into three subbands: (1) 6.6$-$12 nm, (2) 11$-$17 nm, and (3) 16$-$30 nm. A multilayer structure based on Mo and B4C materials with period $d = 6.5$ nm and number of periods $N = 60$ was synthesized for the first subband. This structure provides reflection coefficients in excess of 12% with spectral selectivity $\delta\lambda = 0.1-0.25$ nm within the 6.6$-$12 nm range. A structure based on Mo and Be materials with period $d = 9.83$ nm and number of periods $N = 50$ was fabricated for the second subband. This structure provides reflection coefficients in excess of 30% with spectral selectivity $\delta\lambda = 0.4-1.0$ nm within the 11$-$17 nm range. A structure based on Al and Be materials with period $d = 18.2$ nm and number of periods $N = 40$ was produced for the third subband. This structure provides reflection coefficients in excess of 15% with spectral selectivity $\delta\lambda = 0.8-1.0$ nm within the 16$-$30 nm range.

Calibration curves of correspondence between the mirror rotation angle and the radiation wavelength, the peak reflection coefficient, and the spectral width of the Bragg maximum were obtained for each mirror based on the results of measurements at a synchrotron and verification with a laboratory reflectometer. Thus, the validation of reflective characteristics of multilayer mirrors should allow one both to establish a unique correspondence between the reflection angle and the radiation wavelength and to measure the absolute intensity of radiation from a source at a given wavelength with the use of an SXR and EUV radiation detector that was tested earlier.

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Conflict of interest

The authors declare that they have no conflict of interest.

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