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极紫外宽带 Mo/Si 非周期多层膜偏振光学元件

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摘要：研究了极紫外宽带多层膜偏振光学元件，包括反射式检偏器与透射式相移片。基于 Mo/Si 非周期多层膜结构，采用解析与数值优化相结合的方法进行了多层膜的设计；采用磁控溅射技术制备了多层膜。利用 X 射线衍射仪对非周期多层膜的结构进行了表征，利用德国 BESSY-II 同步辐射实验室的偏振测量仪对多层膜的偏振特性进行了测试。测量结果表明，在 13～19 nm 波段，s 偏振分量的反射率高于 15%；在 15～17 nm 波段，获得了 37% 的反射率。宽带多层膜同样可作为宽角偏振光学元件，在 13.8～15.5 nm 波段，宽带透射相移片的平均相移为 41.7°。采用所研制的宽带多层膜相移片与检偏器，建立了宽带偏振分析系统，并对 BESSY-II 的 UE56/1 PGM1 光束线的偏振特性进行了系统研究。这种宽带多层膜偏振光学元件可以极大地简化极紫外偏振测量。

关　键　词：偏振光学元件；多层膜；相移片；检偏器；极紫外；同步辐射
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Broadband aperiodic Mo/Si multilayer polarization elements for EUV region

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Abstract: Broadband Mo/Si multilayer polarization optical elements were developed for the extreme ultraviolet (EUV) region, including a reflective analyzer and a transmission phase retarder. These multilayers were designed by a combined analytical/numerical method based on an aperiodic stack. Then these aperiodic multilayers were fabricated using direct-current magnetron sputtering technology. The multilayer structures were measured by an X-ray Diffractometer (XRD) working at the Cu-

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Kα line, and the polarization response was characterized by the polarimeter on the UE56/1-PGM1 beamline at BESSY-II, in Berlin. The measured s-polarized reflectivity is higher than 15% over the 13～19 nm wavelength range, and nearly constant s-reflectivity, up to 37%, is observed over the 15～17 nm wavelength range. Furthermore, these aperiodic multilayers show high s-reflectivity and polarization over a wide angular range at fixed wavelength. The measured phase shift is 41.7° over the 13.8～15.5 nm wavelength range. Using an aperiodic transmission phase retarder and a reflection analyzer, a complete broadband polarization analysis system was developed. The polarization properties of the synchrotron radiation from the beamline UE56/1 PGM1 at BESSY-II were systematically characterized in the 12.7～15.5 nm wavelength range by this newly developed broadband polarization analysis system. This kind of broadband multilayer polarizing elements can be used in EUV polarization measurements and will greatly simplify experimental arrangements.

Key words: polarization element; multilayer; phase retarder; polarimeter; extreme ultraviolet; synchrotron radiation

1 Introduction

For polarization-sensitive studies, such as circular dichroism spectroscopy, spin-polarized photoelectron spectroscopy and spectroscopic ellipsometry, accurate evaluation of the polarization state of the radiation is necessary, which requires polarization optical elements, such as analyzer and phase retarder. In extreme ultraviolet (EUV) and soft X-ray regions, periodical multilayers are commonly used in polarization study when they work at the quasi-Brewster angle. However, because of the narrow spectral bandwidth of a periodic multilayer, the multilayers must be changed or rotated to perform broadband polarization analysis. In order to improve this situation, Wang has proposed the design of broadband polarized elements utilizing aperiodic multilayers, including a reflective analyzer[1-4] and transmission phase retarder[5-6]. All the aperiodic multilayers were designed by using a combined analytical/numerical method and prepared by the magnetron sputtering system in Tongji University. Their polarization performance was characterized by the high-precision polarimeter at BESSY-II, in Berlin, Germany. This kind of aperiodic multilayer can work in a broad spectral bandwidth at fixed Brewster angle, or exhibit a wide angular range at fixed wavelength. Hence these broadband multilayer polarization optical elements will greatly simplify experimental arrangements in EUV polarization measurement. The design, fabrication and characterization of aperiodic multilayers have been described previously[1-6]. This article will summarize the Mo/Si broadband polarization elements and their application in broadband polarization analysis.

2 Design and preparation

The design of broadband multilayers for polarization analyzers requires determination of the following parameters: material combination, incident angle and layer thickness distribution. The best material combination for a multilayer is to form smooth and abrupt interfaces with high optical contrast and low absorption. In the 12.4～20 nm wavelength range, just above the Si L-absorption-edge, molybdenum (Mo) and silicon (Si) provide a suitable material combination. At the quasi-Brewster angle, the difference between the s- and p-reflectivity is largest, for which a reflective analyzer can be obtained. Since the complex refractive indices of all materials are very close to unity in the EUV range, the quasi-Brewster is close to 45°. The polarization degree P of the beam reflected from a multilayer is determined in the usual manner from

$$P=\frac{R_s-R_p}{R_s+R_p}\ , \tag{1}$$

where, R_s and R_p are the reflectivities for s- and p-polarized radiation, respectively. In the design of a reflective multilayer analyzer, the optimization of the layer thickness distribution is achieved by minimizing the Merit Function (MF),

$$\mathrm{MF}=\frac{1}{m}\sum_{j=1}^{m}[1-P(\lambda_j)]^2, \qquad (2)$$

where the summation is over a selection of discrete wavelengths in the desired range. The layer thickness distribution is considered as an independent variable. During the recursive optimization, only randomly selected layer thickness changes that decrease MF are retained, finally leading to an optimized layer thickness distribution that provides a minimum value of MF. For the wide angular multilayer analyzer, the optimization is achieved by minimizing the MF

$$\mathrm{MF}=\frac{1}{m}\sum_{j=1}^{m}(1-P(\theta_j))^2, \qquad (3)$$

where the summation is over a selection of discrete angles in the desired range.

The phases of the transmitted s(Φ_s) and p (Φ_p) electromagnetic fields can be calculated by following the formalism of Vidal and Vincent[7], in which the phase shift $\Delta\Phi=\Phi_s-\Phi_p$ is evaluated as a function of wavelength, grazing angle, optical constants of the materials, number of layers and their thicknesses. Initially, the published criteria for selecting the material and the number of bi-layers were used to satisfy both the maximum phase shift and the transmission intensity[8]. Then, the grazing angle was set in the region between the Bragg peak and the total reflection[9] at which the phase shift is maximum. The numerical optimization method was based on the minimization of the MF

$$\mathrm{MF}=\left(\frac{1}{n}\sum_{j=1}^{n}(\Phi_0-\Delta\Phi(\lambda_j))^2\right)^{1/2}, \qquad (4)$$

where $\Delta\Phi(\lambda_j)$ is the calculated phase retardation at wavelength λ_j and Φ_0 is the desired phase shift.

After design, all the Mo/Si aperiodic multilayers were fabricated by using a high vacuum direct current magnetron sputtering deposition system (JGP560C, made in China)[10-11] with targets of Mo (purity 99.95%) and Si (99.999%) in Ar (99.999%) gas. The reflective multilayers were deposited onto 20 mm×30 mm silicon substrates. The transmission multilayers were deposited on silicon nitride (Si_3N_4) membranes with thickness of 100 nm and size of 5 mm×5 mm. In order to calibrate the deposition rate of each sputtering target and determine the multilayer structure, the multilayers were measured using small-angle X-ray diffraction (D1 system, made by Bede Ltd., UK) working at the copper K_α line (0.154 nm)[1-6,11-12].

3 Measurement results and discussion

3.1 Reflective Mo/Si multilayer analyzers

The optical performance of our aperiodic multilayer polarization elements was evaluated by using the high-precision, 8-axes ultra-high vacuum soft X-ray polarimeter on the beamline UE56/1-PGM-1 at BESSY[10]. The polarimeter can be used for the characterization of reflection or transmission properties as well as the polarizing and phase retarding properties of any optical element. Horizontal linearly polarized undulator radiation was used to characterize these reflective Mo/Si multilayer analyzers with different spectral bandwidths: 13～19 nm, 14～18 nm and 15～17 nm. Fig. 1 shows the measured results and the summary is given in Tab. 1. All the analyzers were designed for a grazing incidence angle of 50°. The design data are shown for comparison. The measurements show that (a) the s-reflectivity was between 15% and 27%, with a mean of 18% in the 13～19 nm wavelength range, (b) the s-reflectivity varied from 17% to 25% with a mean of 21% in the 14～18 nm range, and (c) an almost constant s-reflectivity of ≈37% was obtained in the 15～17 nm range. The measured p-reflectivities were very low in all cases. The measured s-reflectivities are smaller than the calculated values due to interfacial roughness and diffusion.

Tab. 1　Design parameters and calculated and measured performance of Mo/Si multilayer analyzers for different spectral bandwidths (errors are rms values)

Sample	R_s_mean (%)		R_p_mean (%)		P_mean	
	calc.	meas.	calc.	meas.	calc.	meas.
(a) 13～19 nm	30.4±1.2	18.2±3.6 (15－27)	0.24±0.16	0.20±0.16	0.985	0.980
(b) 14～18 nm	35.0±0.1	21.1±2.5 (17－25)	0.18±0.14	0.16±0.16	0.990	0.986
(c) 15～17 nm	50.0±0.2	36.6±0.7 (36－38)	0.17±0.07	0.24±0.08	0.993	0.987

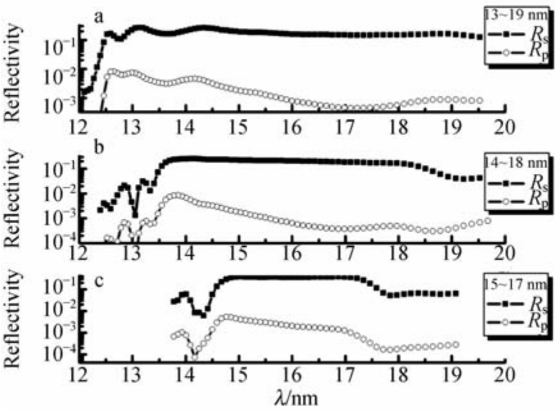

Fig. 1　Measured s- and p- reflectivities of Mo/Si multilayer analyzers optimized for constant reflectivities over the wavelength ranges 13 ～19 nm (a), 14～18 nm (b) and 15～17 nm(c).

Aperiodic multilayer analyzers not only exhibit broad spectral widths at their design angles, but can also be used at nearby angles. In order to demonstrate this, the multilayer (c) shown in Fig. 1 was also measured at grazing incidence angles of 45° and 48°. The measured s- and p-reflectivities are shown in Fig. 2 and compared with those at 50°. It can be seen that the reflectivity shifts to shorter wavelengths when the grazing incidence angle decreases. The range is 15～17 nm for a grazing incidence angle of 50° (as designed), shifts to 14.5～16.5 nm at 48° and to 13.8～15.8 nm at 45°, in keeping with the Bragg equation.

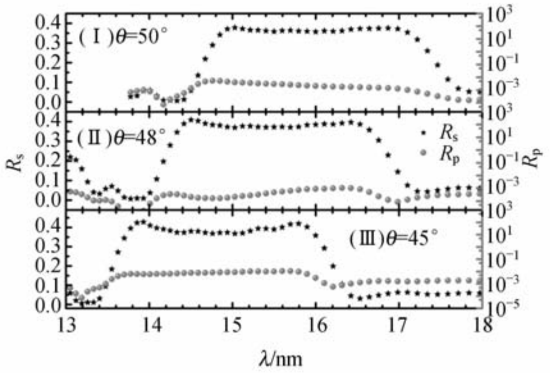

Fig. 2　Measured s- and p- reflectivities of the analysis shown in Fig. 1(c) as functions of the wavelength at grazing incidence angles of 50° (design angle), 48° and 45°

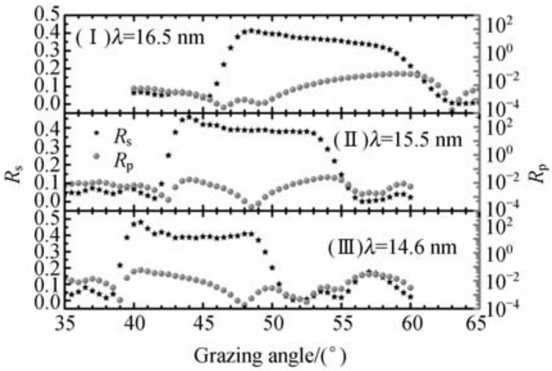

Fig. 3　S- and p-reflectivities for broadband Mo/Si multilayer analyzer as function of grazing incident angle at different wavelengths of 16.5 nm (Ⅰ), 15.5 nm (Ⅱ), and 14.6 nm (Ⅲ).

It follows from the Bragg equation that if a multilayer mirror is designed to reflect over a range of wavelengths at a fixed angle，it will also reflect over a range of angles at a fixed wavelength. The s- and p-reflectivities of the sample (c) shown in Fig. 1 were also measured at different wavelengths：(Ⅰ) $\lambda=16.5$ nm，(Ⅱ) $\lambda=15.5$ nm and (Ⅲ) $\lambda=14.6$ nm. As shown in Fig. 3，aperiodic multilayers not only exhibit broad spectral widths at the design angle，but also can be used at nearby angles. At a wavelength of 15.5 nm，the s-reflectivity is flat and as high as 36.6% from 43° to 54°，and the p-reflectivity is symmetric in this range (Fig. 3Ⅱ).

3.2 Transmission Mo/Si multilayer phase retarder and complete polarization analysis

Mo/Si multilayers deposited on transmittance Si_3N_4 membranes can be used as phase retarders. The performance of the phase retarder was evaluated using the high-precision，ultra-high vacuum eight-axis polarimeter on beamlineUE56/1-PGM1 at BESSY-II. In order to simplify the polarization measurements，a broadband reflective analyzer was also used in the experiment[5]. In order to decrease the fitting error，the s- and p- component reflectivities of the analyzer were measured directly. The measured s-reflectivity is 13%～25% in the wavelength range of 12.5～15 nm at the quasi-Brewster angle of 47.5°，and the reflection ratio R_p/R_s is less than 0.01，which is small enough to allow the analysis of the complete polarization state of an EUV beam. The horizontally polarized radiation was used to characterize the transmission of the phase retarder. A full polarization analysis was performed by recording the intensity behind the phase retarder and analyzer at four different analyzer azimuth angles (β) (0°，45°，90°，and 135°) and for 19 phase retarder azimuth angles (α)，corresponding to rotation over 180°[10,13-15].

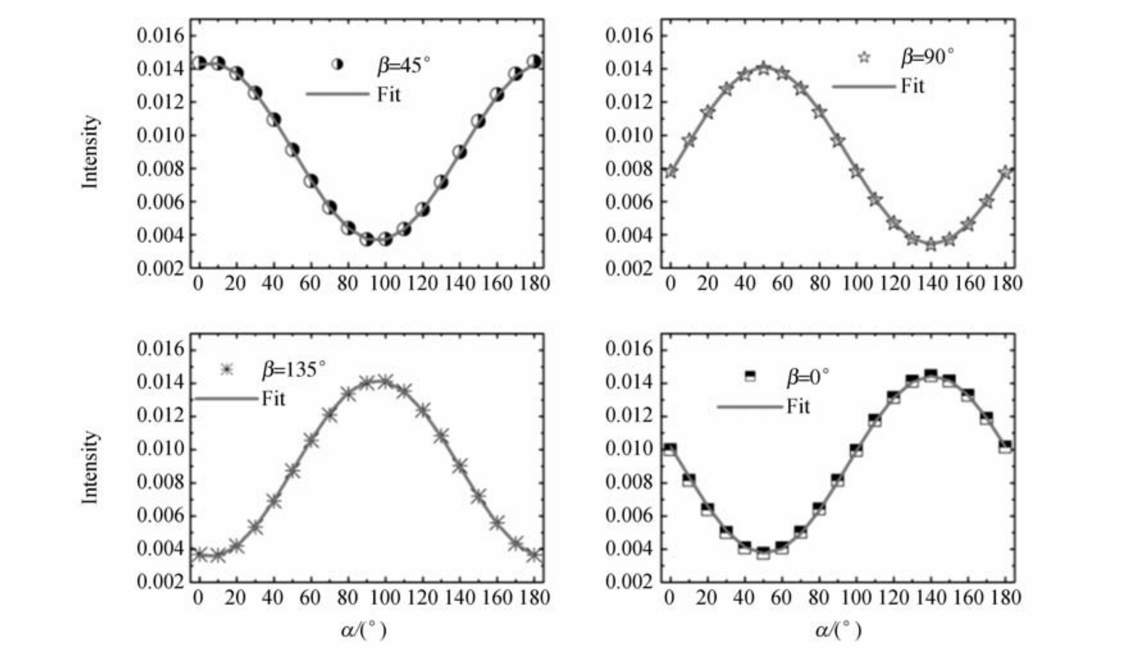

Fig. 4 Polarization measurements with Mo/Si multilayer combination of phase retarder and analyzer at wavelength of 15 nm，showing the angular distribution of the transmitted intensity as a function of the phase retarder azimuthal angle α for four settings of the analyzer azimuthal angle β. The scale factor F，three fitted Stokes-Poincaré parameters P_1 (one direction of linear polarization)，P_2 (orthogonal direction)，P_3 (circular polarization) of the incident radiation and the polarizing properties of the two optical elements are：$F=16.5\pm0.5$，$P_1=-0.001\pm0.001$，$P_2=-0.089\pm0.002$，$P_3=-0.999\pm0.001$，$\Delta\Phi=(38.4\pm0.2)°$，$T_p/T_s=0.910\pm0.001$，$R_p/R_s=0.019\pm0.003$.

A typical polarimeter spectrum of the transmitted intensity normalized by the incident intensity at a wavelength of 15 nm is shown in Fig. 4. These data were analyzed by using the least-squares fitting method with seven free parameters, i. e., three Poincaré parameters (P_1, P_2, P_3) equal to the Stokes′ parameters normalized with respect to the total intensity S_0 ($P_i = S_i/S_0$), a scale factor $F = S_0/I_0$ (I_0 is the normalized intensity of incident beam), the transmission and reflection ratios T_p/T_s and R_p/R_s for the phase retarder and analyzer, respectively, and the phase shift $\Delta\Phi$.

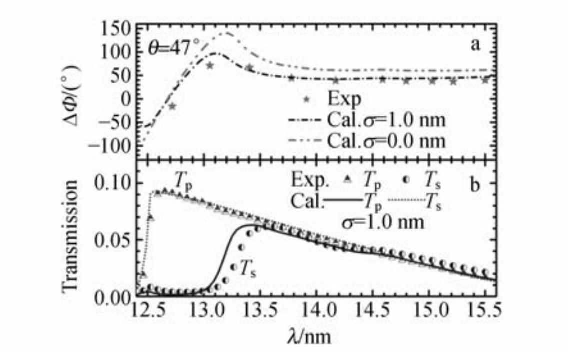

Fig. 5　(a) Calculated (with interlayer roughnesses $\sigma = 0$ nm and 1 nm) and fitted phase shifts. (b) Calculated (with roughness 1 nm) and measured transmissions T_s and T_p as functions of wavelength at a grazing incidence angle of 47°.

The best overall fit, keeping R_p/R_s fixed at the directly measured values, resulted in a phase shift of the aperiodic transmission phase retarder; the fitted results are shown in Fig. 5(a). The measured phase shift decreases from 55.6° to 38.1° with an average of (41.7±4.3)° over 13.8～15.5 nm wavelength range. As shown in Fig. 5(b), the transmission of the phase retarder was also measured at a grazing angle of 47°. The transmission intensity was 6%～2% in 13.5～15.5 nm range with a transmission ratio T_p/T_s of 0.96±0.11. The calculated results with an interface roughness of 1.0 nm are in good agreement with experimental data.

3.3　Broadband polarization analysis of EUV radiation at BESSY-II

As described above, the broadband polarization analysis consists of a broadband transmission multilayer phase retarder and a broadband reflective multilayer analyzer. Using the high precision ultra-high vacuum eight-axis polarimeter on beamline UE56/1-PGM1 at BESSY-II, the complete polarization analysis of synchrotron radiation was performed[6]. The polarization parameters of the radiation were also determined by a least-squares fit to the measured data. The measured Stokes-Poincaré parameters of the radiation as a function of wavelength are shown in Fig. 6. The circularly polarized parameter P_3 is close to unity while the linearly polarized values, with averages $P_1 = 0.007 \pm 0.026$ and $P_2 = -0.053 \pm 0.005$, oscillate around zero over the wavelength range. As the wavelength increases from 12.7 nm to 15.5 nm, the linear polarization parameter P_2 changes from positive to negative with a minimum of −0.14 at 15.2 nm wavelength. The fitted behaviors agree quite well with model predictions of the circularly polarized radiation. The wavelength dependence of the polarization of the synchrotron radiation can thus be characterized by a complete polarization analysis without changing the incidence angles of the broadband phase retarder and analyzer; this can lead to a considerable simplification for such systems.

The UE56 undulators at BESSY-II are elliptical polarizing insertion devices of the Apple-type. The difference to a standard planar undulator is the horizontally split magnet rows above and below the electron orbit. The shifting of these rows produces a helical field at the position of the electron beam causing an elliptical or even circular trajectory. Using these newly developed broadband polarizing elements, the polarization of the radiation from the BESSY-II UE56/1-PGM at 13.1 nm was measured as function of the shift of the magnetic rows. The Stokes-

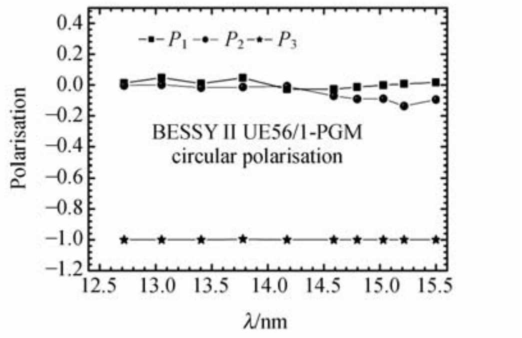

Fig. 6 Stokes-Poincaré parameters (P_1, P_2, P_3) of the circular radiation from the BESSY-II UE56/1-PGM1 beamline as functions of the wavelength, at fixed angles of the Mo/Si broadband phase retarder (45°) and analyzer (47°).

Poincaré parameters are shown in Fig. 7 together with the fitted curves and gap values, which were also changed with the shift in order to fix the energy of the undulator harmonic. The grazing incidence angles of the phase retarder and analyzer were fixed at 45° and 47°, respectively. At the largest shift of the diagonal magnets, the radiation is nearly completely circularly polarized, with $|P_3| \geqslant 0.94$. For the shift with 0 mm, the linear polarization is largest, with $|P_1| = 0.96$. These measurement results are in good agreement with the expected variation from the known undulator parameters.

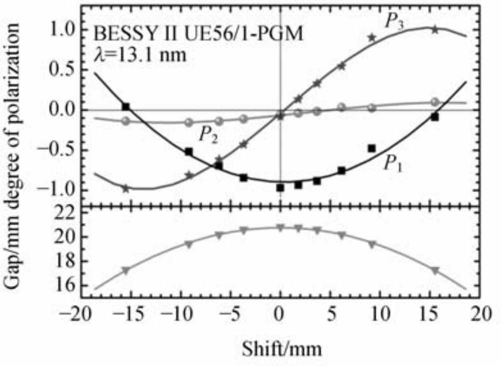

Fig. 7 Measurement of Stokes-Poincaré parameters (P_1, P_2, P_3) of the radiation from the BESSY-II UE56/1-PGM1 beamline and the gap values as functions of the undulator shift-setting at a wavelength of 13.1 nm.

4 Conclusions

Utilizing an aperiodic multilayer, the broadband Mo/Si reflective analyzer and transmission phase retarder have been designed, prepared and measured for EUV region. Their polarization properties were evaluated by using the polarimeter at BESSY-II. The measured results show that the s-polarized reflectivity is higher than 15% over a 13～19 nm wavelength range. The s-reflectivity is reasonably constant, as high as 37% over 15～17 nm wavelength range. The measured phase shift decreases from 55.6° to 38.1° with an average of (41.7±4.3)° over 13.8～15.5 nm wavelength range, sufficient to analyze completely the polarization characteristics of the synchrotron radiation beam. Using an aperiodic transmission phase retarder and a reflection analyzer, a complete broadband polarization analysis system was developed. A complete polarization analysis can be performed in a broadband wavelength range. The polarization properties of synchrotron radiation and these polarizing devices were systematically characterized. Polarized radiation from the BESSY-II UE56/1-PGM1 beamline was characterized as functions of the wavelength and of the undulator settings using the broadband phase retarder-analyzer pair. This system has high potential for the practical control and monitoring of radiation in polarization-sensitive experiments. Furthermore, the design and manufacturing methods for broadband aperiodic multilayer described here are generally applicable to other material pairs, and wavelength ranges.

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