Coherence preservation of synchrotron beams by multilayers

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Abstract. This work discusses the spatial coherence preservation and the uniformity of a synchrotron beam reflected from multilayer based x-ray optics. Experiments were carried out on the ESRF undulator beamline ID06 using direct imaging and the Talbot technique. Several W/B$_4$C multilayers with differing d-spacings were studied with monochromatic light at various photon energies. To understand the respective influence of the underlying substrate and the multilayer coatings, measurements were made under total reflection, at different Bragg peaks, and on the bare substrates. In addition, samples with different substrate quality were compared. In the present study, both the degree of spatial coherence preservation and the visibility of characteristic line structures in the x-ray beam seem to be given by the properties of the underlying substrate.

1. Introduction
Preserving the coherence properties of the x-ray beam is a major concern on 3rd generation synchrotron beamlines [1], in particular for advanced imaging applications. Due to their increased bandpass, multilayer (ML) optics can be an attractive alternative to single crystals, providing about 100 times more photon flux. The coherence of a source of radiation is characterized by its ability to produce interference contrast in space and time. The spatial coherence of an extended, randomly emitting source can be quantified by defining appropriate coherence lengths [2] $L_L$ along the direction of propagation and $L_T$ perpendicular to it.

$$L_L = \frac{\lambda^2}{2 \cdot \Delta \lambda}, \quad L_T = \frac{\lambda \cdot p}{2 \cdot S}$$

(1)

where $\lambda$ is the wavelength, $S$ the lateral source size and $p$ the distance to the source. For synchrotron radiation, $L_L$ can be modified by the monochromator band-pass, while $L_T$ is inversely proportional to the angular source size, $S/p$. The technique of Talbot imaging [3-6] consists of self-imaging of a periodic object along the propagation direction and with a repetition period of $D_T$. In the case of a monochromatic plane incoming wave this so called Talbot distance is given by

$$D_T = \frac{2 \cdot a^2}{\lambda}$$

(2)

where $a$ is the period of the illuminated object itself. When the ideal plane wave is replaced by a set of mutually incoherent plane waves the visibility of subsequent images decays and the intensity ratio of subsequent maxima allows for the calculation of the effective source size according to [5]

$$S = \frac{2.35 \cdot p \cdot a}{\pi \cdot D_T} \sqrt{\ln \left( \frac{I\left(\frac{1}{4}D_T\right)}{I\left(\frac{1}{2}D_T\right)} \right)}$$

(3)

An advantage of the Talbot technique is its independence of absolute intensities and the exact nature of the periodic object. In a real measurement, the source size thus calculated will directly include the effects of any degradation due to optical imperfections of any of the active beamline components.
2. Experimental aspects

All coatings were made using the ESRF multilayer deposition system [7] that is based on magnetron sputtering. Table 1 summarizes the characteristics of the samples under investigation.

Table 1. Overview and characteristics of substrates and ML samples under investigation.

| Sample | ML structure | d-spacing [nm] | \(\sigma(Si)\) [nm] | \(\varepsilon(Si)\) [\(\mu\)rad] | \(\varepsilon(ML)\) [\(\mu\)rad] |
|--------|--------------|----------------|---------------------|-----------------|-----------------|
| #1     | [W/B\(_4\)C\(_{40}\)] | 6.0            | 0.085               | 0.11            | 0.10            |
| #2     | [W/B\(_4\)C\(_{60}\)] | 4.0            | 0.065               | 0.13            | 0.09            |
| #3     | [W/B\(_4\)C\(_{120}\)] | 2.0            | 0.075               | 0.16            | 0.15            |
| #4     | [W/B\(_4\)C\(_{80}\)] | 4.0            | 0.43                | 7.2             | -               |

The MLs #1-3 were deposited on high quality Si substrates. In these cases only half of the substrate was coated to keep the free Si surface as a reference. The ML #4 was coated on a Si block that had been polished inhouse to moderate quality. The RMS surface roughness \(\sigma(Si)\) was measured with a micro-interferometer and the RMS slope error \(\varepsilon\) was obtained with the ESRF Long Trace Profiler.

2.1. X-ray reflectivity measurements

All ML samples were characterized on a laboratory x-ray reflectometer, operating with a microfocus Cu tube at 8048eV and a Ge(111) monochromator and providing a dynamical range of up to \(10^7\). Simulation software based on the Parratt formalism [8] allows for the precise determination of thicknesses, mass densities, and interface widths.

2.2. Talbot imaging setup

All samples were measured on the ESRF undulator beamline ID06. The ML was mounted at a distance \(p = 56\) m from the source and a 2D Si transmission grating with a pitch of 8 \(\mu\)m was placed 65 mm downstream from the ML centre. Most of the experiments were carried out at a photon energy of 15.0 keV, where the expected Talbot distance would be \(D_T = 1549\) mm, leading to visibility maxima at 452 mm and 1227 mm from the ML centre, and separated by a minimum at 840 mm. Samples #1-3 were imaged under total reflection on the bare Si surface, under total reflection on the ML surface, and on the 1\(^{st}\) Bragg reflection.

3. Results

3.1. Multilayer structure and reflectivity

The x-ray reflectivity data of samples #1-3 are summarized in Figure 1. They show spectra with strong higher order Bragg peaks corresponding to interface widths of the order of 0.25 – 0.30 nm RMS.

![Figure 1](https://example.com/figure1.png)

Figure 1. From left to right: specular reflectivity curves of MLs #1, #2, and #3, all taken at 8048 eV. \(\Theta\) denotes the grazing angle of incidence.
3.2. Flat field imaging

A series of flat field images taken at the first Bragg peak at 15.0 keV and at 452 mm from the ML centre, but without grating in the beam, is shown in Figure 2. They are averaged and corrected for the dark-noise background. The respective sample type and angle of incidence are indicated on each image. Depending on the angle, between 30 mm and 90 mm of the sample length are vertically projected into one image.

![Figure 2. Flat field images of MLs #1-3 in Bragg condition. The corresponding angles of incidence are indicated.](image)

All images show a similar stripe contrast that is probably caused by surface figure and slope errors and the related local phase shift. As expected, the modulation frequency seems to depend on the angle of incidence. Projected along the footprint it corresponds to a spatial period of about 1 mm, also observed using surface metrology. These and further images show that neither the photon energy nor the d-spacing seems to have an explicit impact on the contrast. Similar images were taken at the same distance but under total reflection (TR) either on the bare Si or on the ML coating at angles of incidence of 0.10° at 15.0 keV and 0.05° at 30.5 keV. Apart from the compressed footprint there are no significant differences between the 3 MLs or between those taken on the Si and on the ML surface. The 2 nm ML #3 was imaged along the edge of the ML coating and the bare Si substrate (Figure 3). Most of the line features cross the transition zone from the Si to the ML coating without major modifications. This means that the ML deposition does not significantly modify the visibility of stripes. Both their position and contrast seem to be given by the Si substrate alone and are being printed through the ML coating.

![Figure 3. Flat field image of sample #3 under TR along the transition zone between Si (right) and the ML coating (left). Many line features cross the coating edge as indicated by horizontal lines.](image)

3.3. Grating imaging and Talbot analysis

The averaged grating images were divided by the averaged flat field images to normalise for variations of the detector efficiency and intensity across the incident beam. To obtain accurate results, all images were corrected for tilt errors of the grating structures before performing Fourier transforms along both the vertical and the horizontal direction [9].
The so obtained Fourier coefficients of the fundamental grating periodicity (Talbot coefficients) are plotted versus the distance $y$ from the ML. In Figure 4, the vertical Talbot coefficients of MLs #1-3 at 15.0 keV at the 1st Bragg peak (a), under total reflection on the ML (b), and under total reflection on the Si substrate (c) are compared with those from the direct beam. All three MLs show similar curves with maxima and minima near the expected positions and a damping envelope. The corresponding effective vertical source size can be estimated to $S_V = (107 \pm 18) \, \mu m$. The Talbot analysis of ML #4 did not allow for the derivation of reasonable Fourier coefficients.

Figure 4. Vertical Talbot coefficients at 15.0 keV from the 1st Bragg peak (a), under total reflection on the ML (b), and under total reflection on the Si substrate (c). Triangles indicate ML #1, circles ML #2, and squares ML #3. The broken line corresponds to data from the direct beam.

4. Summary
Flat field imaging of various W/B$_4$C MLs has shown a characteristic stripe contrast with a spatial period of the order of 1 mm, irrespective of the chosen Bragg angle, the d-spacing, or the photon energy. Similar observations have been made under TR both on the ML coatings and on the bare Si surfaces. The study of the edge of a ML coated area under TR revealed that both the position and the visibility of stripes do not significantly change when crossing the transition zone. It appears that most features are caused by the substrate alone and are being printed through the ML stack. Talbot imaging indicates a comparable degree of coherence preservation, again irrespective of the chosen Bragg angle, the d-spacing, or the photon energy. Similar findings were made under TR both on the ML coatings and on the bare Si surfaces.

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