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Reflective soft x-ray microscope for the investigation of objects illuminated by laser-plasma radiation

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Abstract. Multilayer mirrors were used in a soft x-ray optical system which formed magnified images of microscopic objects with a resolution of ~ 0.2 μm at the wavelength 20 nm. The system consisted of a laser-plasma source, an x-ray condenser, a Schwarzschild objective with a magnification 20, a set of filters, and a detector. The quality of the x-ray optics and the precision of alignment of the system components made it possible to attain a resolution of ~ 0.2 μm when the full aperture of the objective was used. A single shot in the form of the second harmonic of an Nd laser, generating pulses of ~ 0.5 J energy and ~ 1.5 ns duration, was sufficient for exposure.

1. Introduction

An important task in modern x-ray microscopy is the attainment of spatial resolution of the order of the radiation wavelength, which corresponds to the diffraction limit in optical systems with a large numerical aperture. In the wavelength range 3 – 30 nm the most promising are the systems with x-ray optical components of two types: normal-incidence multilayer mirrors and zone plates. Particularly convenient are sliced zone plates fabricated by the method of multilayer sputtering on a thin wire or filament from which a zone plate of the required thickness is then cut [1 – 3].

For physical and technological reasons, the working areas of such mirrors and zone plates differ by six orders of magnitude. A mirror diameter is usually 50 – 150 mm and that of a zone plate is 100 – 300 μm. Naturally, mirrors and zone plates have their own ranges of application and the method of their use is different. On the other hand, there is some competition between them in the attainment of the best resolution. However, in many applications other characteristics are as important as the resolution: they include the field view, the effective area, the focal length, etc.

We shall now give a description, and report studies, of a Schwarzschild microscope with the magnification $M \approx 21$ at wavelengths ~ 20 nm. Our aim was to develop a technology for the fabrication of components of such an x-ray microscope and for its alignment, and to test experimental methods in which reflection x-ray optics is used in imaging of small nonluminous objects with features of submicron size.

2. Schwarzschild x-ray objective

Our microscope included a laser-plasma source, an x-ray condenser for the illumination of an object, a Schwarzschild objective, a set of filters, and a detector (Fig. 1). The Schwarzschild objective consisted of two spherical mirrors and was capable of compensating for third-order axial aberrations when an object occupied a certain position.

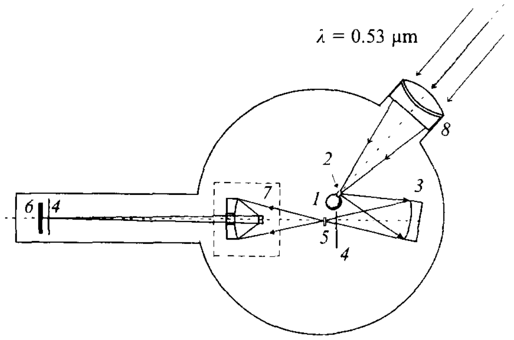

Figure 1. Schematic diagram of the soft x-ray microscope: (*1*) bulk rhenium target; (*2*) laser plasma; (*3*) condenser; (*4*) aluminium filters, 0.4 – 0.5 μm thick; (*5*) test object; (*6*) UF-4 photographic film; (*7*) Schwarzschild objective; (*8*) focusing objective.

In spite of the fact that work on the Schwarzschild x-ray objectives has been going on for over a decade [4 – 6], the spatial resolution achieved so far is still considerably greater than the x-ray wavelength. This is due to the stringent requirements in respect of the precision of fabrication of mirrors of spherical shape, their alignment, and quality of multilayer coatings.

At present the development and applications of the Schwarzschild x-ray objectives are proceeding along several directions. The first direction is the development of scanning microscopes [7 – 9] in which the most important characteristic is the resolution on the optic axis (representing the size of the spot), which is of the order of 0.1 μm.

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Second, the Schwarzschild objectives are used as the main part in many currently being developed x-ray projection lithography systems [4, 10–16]. In addition to the required spatial resolution of ~ 0.1 μm, it is necessary to ensure that such a system contains $10^8 - 10^{10}$ elements, so that the field of view is important. Third, there have been relatively few investigations in which a Schwarzschild objective is used in the traditional optical microscope configuration: it creates a magnified image of an object on an x-ray detector. The object may be self-luminous (laser plasma [17, 18]) or it may be illuminated with radiation from a synchrotron [19], an x-ray tube [20], an x-ray laser [21], or a laser plasma [22].

We shall now give the main relationships which apply to a Schwarzschild objective. If R_1 and R_2 are the radii of concave and convex mirrors with a shared centre of curvature, the compensation of the third-order axial aberrations occurs when the object is located at a distance Z_0 from the centre of curvature of the mirrors [23]:

$$Z_0 = \frac{R_1 R_2}{R_1 - R_2 + \sqrt{R_1 R_2}} .$$

The magnification of the system is then

$$M = \frac{R_1 - R_2 + \sqrt{R_1 R_2}}{R_1 - R_2 - \sqrt{R_1 R_2}} .$$

In the paraxial approximation we can regard a concentric Schwarzschild objective as equivalent to a thin lens located at the shared centre of curvature of the mirrors and characterised by the focal length

$$F = -\frac{R_1 R_2}{2(R_1 - R_2)} .$$

We used a Schwarzschild objective with the following parameters: the magnification $M \approx 21$, the radius of curvature of the large mirror $R_1 = 100$ mm, the diameter of the optical window $D_1 = 50$ mm, the radius of curvature of the small mirror $R_2 = 35$ mm, the diameter of the small mirror $D_2 = 10.6$ mm, the numerical aperture $N_a = 0.19$, and the focal length $F = 26.9$ mm. The substrates of the spherical mirrors were made of KU-1 fused quartz. The rms deviation of the shape of the substrates from spherical did not exceed ~ 5 nm over the whole working area, which matched the precision of the measuring apparatus we used. The residual transverse axial aberrations δ were calculated by the SURF computer program [22] and they amounted to ~ 0.06 μm in the concentric Schwarzschild configuration.

A multilayer Mo–Si coating was deposited by the method of dc magnetron sputtering [24] simultaneously on both mirrors in the Schwarzschild objective and on the condenser. The reflectivity of the mirrors was enhanced by selecting molybdenum as the topmost layer for all the optical components. The molybdenum was itself protected by a thin (1.5–2.0 nm) silicon film, which prevented degradation with time [25]. The period of the deposited coating was deduced from the reflection curve obtained for grazing incidence at the wavelength of the K_α copper line when the radiation was incident on an auxiliary plane mirror, which was fabricated at the same time as the spherical mirrors. The coating period was $d = 9.89$ nm, the fraction of the Mo layer in the period was 0.34, and the number of periods was 20.

At the working wavelength of $\lambda \sim 20$ nm, our technology usually ensured that the reflectivity of the spherical mirrors was 20%–25% [26]. No special measurements were made of the reflectivity of the components of this objective or of the condenser.

3. Optical alignment of the objective

The alignment of a Schwarzschild objective usually requires auxiliary high-quality optics with a relatively large aperture (which should be at least ~ 0.2). A special difficulty arises in locating the centres of curvature of the mirrors, which should coincide to within ~ 1 μm in a plane perpendicular to the optic axis of the system. We developed a system for optical alignment of a Schwarzschild objective in which the small mirror was in the shape of a meniscus.

An expanded and collimated He–Ne laser beam is focused by a micro-objective (*4* in Fig. 2) in a plane (*10*) and, after reflection from the two spherical mirrors of the objective (*5* and *6*), it reaches a screen (*9*). The focal plane (*10*) is imaged by the micro-objective (*4*), a beam-splitting cube (*3*), and a long-focus objective (*7*) in another plane (*11*). Then a second micro-objective (*3*) projects the image on the screen (*9*). The overall magnification of the system is about 5000. If the centres of curvature of the mirrors are located near the focal plane (*10*), the screen (*9*) shows in general three focal distributions of the laser radiation reflected by the mirrors (*5* and *6*) of the objective. Displacement of one of the mirrors (*5* and/or *6*) makes it possible to ensure that the centres of curvature of the two mirrors coincide. The error of coincidence of the centres in the focal plane is $\sim 0.2 - 0.5$ μm. Along the optic axis the coincidence error is governed by the length of the caustic of the small mirror and amounts to $\sim 10 - 15$ μm.

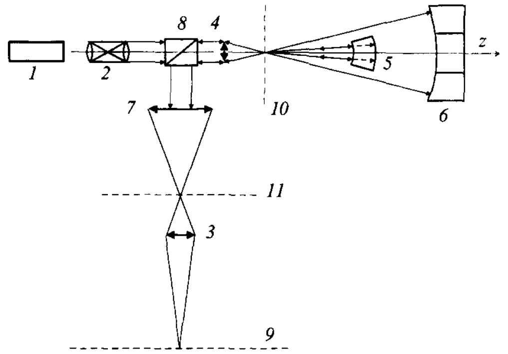

Figure 2. System used to align a Schwarzschild objective: (*1*) He–Ne laser; (*2*) telescope; (*3, 4*) micro-objectives; (*5, 6*) Schwarzschild objective mirrors; (*7*) long-focus objective; (*8*) beam-splitting cube; (*9*) screen; (*10*) focal plane; (*11*) imaging plane.

The two mirrors forming the objective are supported by a metal casing: the large mirror is immobile and the small mirror has two degrees of freedom in a plane perpendicular to the optic axis of the objective. The centres of curvature of the mirror are made to coincide along the optical axis by calibrated rings placed inside the objective casing.

4. Experimental methods and discussion

The operation of the Schwarzschild objective in its working range ($\lambda \approx 20$ nm) was tested by a method we used earlier [22] (see Fig. 1). Our x-ray source was a plasma formed by focusing, on a bulk rhenium target, laser radiation with the wavelength $\lambda_0 = 0.53$ µm, emitted in the form of pulses of 1.5 ns duration and with the maximum pulse energy up to 20 J. Our test objects, used to determine the spatial resolution of the objective, were two gold transmission gratings: one with a period of 1.4 µm and a gap 0.5 µm wide and the other with a period of 0.2 µm and a gap of less than 0.1 µm.

Preliminary alignment to ensure the sharpness of the images of test objects was carried out in the visible range. Fine alignment in the x-ray range involved displacement of a film cassette along the optic axis of the system after each exposure when the test object was kept immobile. The construction of the cassette was such that up to eight images could be recorded on one photographic film without disturbing the vacuum. The size of each image was 3 mm × 3 mm; it was governed by the size of an aluminium filter (*4* in Fig. 1) placed immediately in the front of the film. The high brightness of the laser-plasma source [27] ensured that images with a normal density were recorded in one laser shot of 0.5 J energy.

Fig. 3 shows photographs of our test objects. Fig. 3b reveals clearly the defects in fabrication of the grating with the 0.2 µm period. The irregularity of the grating was confirmed independently by electron microscopy. Therefore, x-ray microscopy may be used to monitor the quality of samples at the submicron level. The thickness of the object can be considerably greater than in electron microscopy, because the range of x-ray photons in matter is much greater than the depth of penetration of electrons.

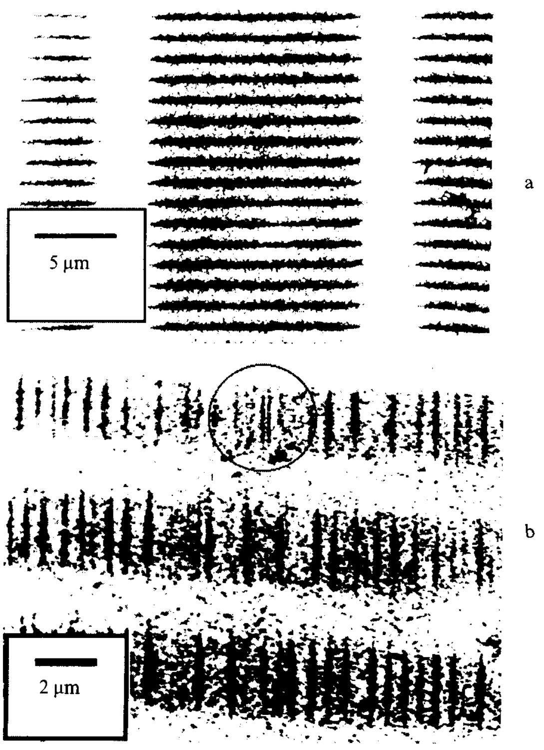

Figure 3. Soft x-ray images of gold gratings with periods of 1.4 µm (a) and 0.2 µm (b). Fig. 3b was obtained after partial elimination of the distortions contributed by the photographic film.

In contrast to our previous experiments [22], the high quality of the mirrors and the better alignment made it possible to utilise the full aperture of the objective (i.e. the numerical aperture of ~0.2) and to attain a spatial resolution of 0.2 µm (Fig. 3b), which was possibly limited by the grain size of our UF-4 photographic film.

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