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Schwarzschild soft-x-ray microscope for imaging of nonradiating objects

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A soft-x-ray optical system based on multilayer mirrors was designed and fabricated for the production of magnified images of micro-objects with a spatial resolution of ~0.2 μm at a wavelength $\lambda \approx 20$ nm. The system consists of a laser-produced plasma source, a condenser mirror, a 20× Schwarzschild objective, a filter set, and a detector. The quality of the x-ray optics and the precision of the system adjustment enabled us to achieve, for the first time to our knowledge, ~0.2-μm resolution using the full aperture (numerical aperture 0.2) of the objective and a single shot of a frequency-doubled Nd laser (pulse energy ~0.5 J, pulse duration ~1.5 ns).

A number of papers have been published on x-ray scanning and imaging microscopes based on Schwarzschild objectives consisting of two mirrors covered with multilayer reflecting coatings.[1–12] A Schwarzschild microscope can be used for investigation of radiating (hot plasma)[2,6,10] or nonradiating[7–9,12] objects, which is especially valuable for various applications in biology, microanalysis, and medicine. Four years ago at AT&T Bell Laboratories a Schwarzschild objective of numerical aperture $N_A = 0.07$ was used to demonstrate the feasibility of 0.05-μm projection lithography.[13]

The spatial resolution obtained with large-aperture ($N_A > 0.2$) Schwarzschild imaging microscopes is still far from the diffraction limit for x rays. The main reasons are errors in the mirror's figure and misalignment of the microscope elements. In this Letter we present the results of the development of our soft-x-ray microscope designed for the investigations of nonradiating objects, which was started two years ago.[9]

The x-ray microscope consists of (see Fig. 1) a laser-plasma x-ray source, the object illumination system, an x-ray Schwarzschild objective, and a detector. We produced the laser plasma used as an x-ray source by focusing the second-harmonic radiation of a Nd:glass laser onto a massive Re target. The pulse duration was 1.5 ns, the maximum energy as high as 20 J, and the focal spot diameter approximately 20 μm. It is essential that the parameters of the x-ray laser plasma source and the x-ray optics throughput allow us to produce the image using only one laser pulse of nanosecond duration.

The object illumination system was designed to filter the working wavelength range ($\lambda \approx 20$ nm) and to steer it onto the object. It consists of a multilayer spherical mirror as a condenser and an Al filter of 0.4-μm thickness. The condenser differs from the large objective mirror only by an additional carbon layer with 10-nm thickness deposited in order to cutoff the UV radiation. The influence of this carbon layer on the wavelength dependence of the microscope throughput has been evaluated.[9]

The x-ray objective consists of two spherical multilayer mirrors with the parameters given in Table 1 and has a magnification $M \approx 20$. Multilayer Mo–Si coating was deposited by dc sputtering and was protected

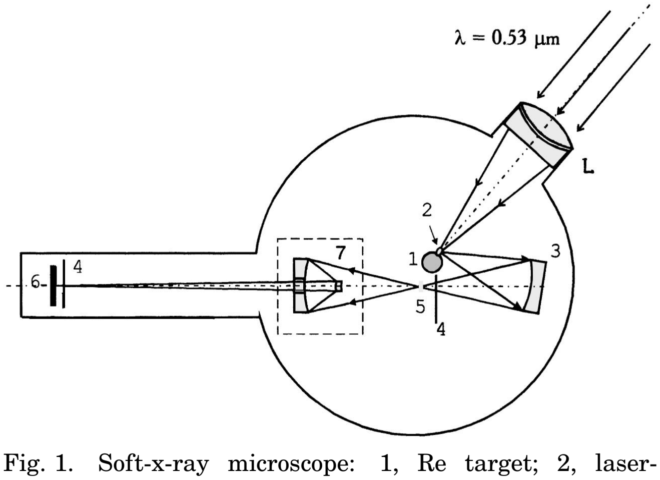

Fig. 1. Soft-x-ray microscope: 1, Re target; 2, laser-plasma x-ray source; 3, condenser mirror; 4, Al filters of thicknesses 0.4–0.5 μm; 5, test object; 6, film UF-4; 7, Schwarzschild objective; L, focusing objective.

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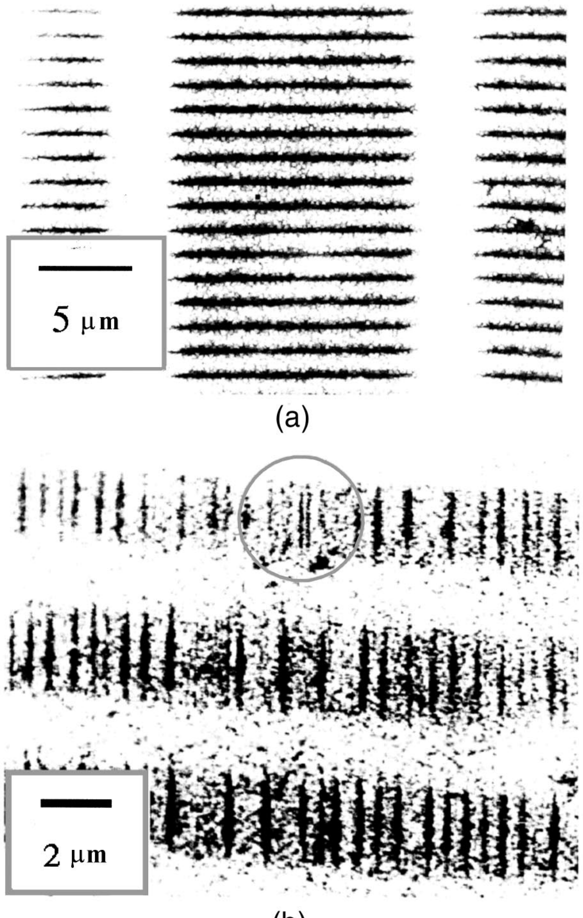
Table 1. Main Parameters of the Schwarzschild Objective Used

Magnification M	21.26
Focal length F (mm)	26.9
Large mirror diameter D_1 (mm)	50
Large mirror radius of curvature R_1 (mm)	100
Small mirror diameter D_2 (mm)	10.6
Small mirror radius of curvature R_2 (mm)	35
Hole diameter D_h (mm)	10.8
Mirror separation S (mm)	65
Object–image distance Z (mm)	627.59



(a)

(b)

Fig. 2. Soft-x-ray images of Au gratings: (a) a grating with period 1.4 μm, (b) a grating with period 0.2 μm. To produce Fig. 3(b) the image was computer processed in order to decrease distortions caused by film imperfections.

from aging degradation by a top, thin Si layer of 1.5–2 nm. The period of multilayer coating was measured to be $d = 9.89$ nm, the number of bilayers $N = 20$, and the portion of the Mo layer in the period $\beta = 0.34$. The reflection coefficient of the mirrors was not measured for this microscope, but recent investigations of similar mirrors deposited with the same technique estimated the reflection coefficient value to be 20–25%.[14]

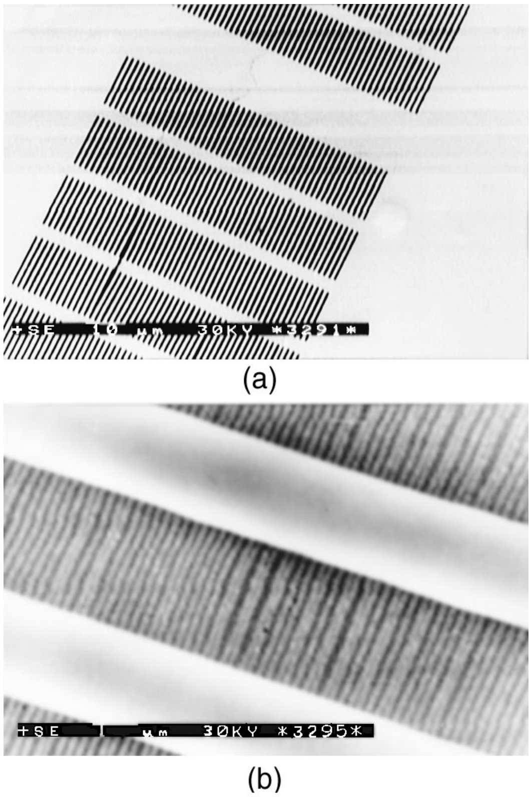
The mirrors and the sample holder were assembled and fixed in the Schwarzschild configuration inside a special metal housing. The housing allows one to adjust the objective first in the visible and then in the x-ray range. The microscope alignment is described in more detail in Ref. 15. The technology of objective construction has been improved so that we can achieve better resolution than in the previous experiment.[9] The accuracy of the mirrors' shape was measured to be approximately 5 nm (rms). The accuracy of mirror positioning along the optical axis and in the perpendicular direction was 10–15 μm and 0.2–0.5 μm, respectively.

The x-ray film UF-4 was used as a detector in our experiments. It enables us with one laser pulse of energy ~0.5 J to observe the details of the test objects with sizes down to 0.2 μm.

For testing the microscope in the working wavelength of $\lambda \approx 20$ nm, we used the method described in Ref. 9. To determine the spatial resolution of the microscope we used two Au gratings as test objects: one had a period of 1.4 μm and a slit width of 0.5 μm and the other had a period of 0.2 μm and a slit width of <0.1 μm. For production of the best quality we made several (as many as eight) shots to obtain images for different positions of the film. The image size was limited to 3 mm × 3 mm by the window of the Al filter located close to the film (see Fig. 1).

Figure 2 shows soft-x-ray images of the test objects. The image shown in Fig. 2(b) clearly reveals the defects of the 0.2-μm-period grating. The irregularities of this grating were confirmed independently by a scanning electron microscopy technique [see Fig. 3(b)].

Thus the soft-x-ray microscope proves to be an effective tool for controlling quality of submicrometer structures in various samples. The samples can be much thicker than those for transmission electron



(a)

(b)

Fig. 3. Images of the same Au gratings as in Fig. 2 but produced by the scanning electron microscope: the grating periods are (a) 1.4 μm and (b) 0.2 μm.

microscopy because of the larger path length of x-ray photons in the matter.

In summary, the soft-x-ray microscope designed for $\lambda \approx 20$ nm radiation with numerical aperture $N_A = 0.19$ and magnification $M \approx 20$ shows 0.2-μm spatial resolution when its full aperture is used. For the first time to our knowledge, this was achieved with only one shot of a 0.5-J pulse of a frequency-doubled Nd:glass laser. These results look promising for application of soft-x-ray microscopy in medicine, biology, and microanalysis. The next step will be the development of a tabletop soft-x-ray microscope facility based on a commercially available repetition-rate laser.

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