SOFT X-RAY IMAGING ZONE PLATES WITH LARGE ZONE NUMBERS FOR MICROSCOPIC AND SPECTROSCOPIC APPLICATIONS

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Holographically made zone plates are described. Imaging properties and spectrometric applications are discussed. Experimental results with soft X-radiation are given.

1. Introduction

It is well known that the refractive index of all materials in the soft X-ray region is slightly less than unity. Therefore it is impossible to construct normal refractive optics. There are, however, two other possibilities for imaging in this spectral region, namely, reflectance optics with grazing incidence and diffraction optics. Whereas in the field of X-ray astronomy reflectance optics with grazing incidence is widely used, in the field of X-ray microscopy diffraction optics is more suitable.

2. Holographically made zone plates with large zone numbers

A special case of diffraction optics are zone plates, i.e., circular gratings with radial increasing line density. Zone plates with large zone numbers can be realized holographically by superposition of two spherical waves or one spherical wave and one plane wave [1, 2]. This interference pattern is produced by using the radiation of an Ar^+ (457.9 nm) or a Kr^+ (350.7 nm) ion laser. By subsequent preparation the interference pattern is converted into a zone plate consisting of opaque gold rings on a thin organic layer transparent to soft X-rays.

The optical path difference between rays from P to Q via two subsequent zones with the radii r_n and r_{n-1} is $\lambda/2$, this means

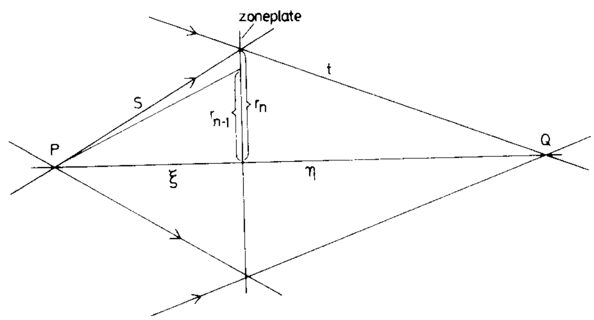

Fig. 1. Principle of zone plate construction.

$$\xi + \eta = s + t - n\lambda/2, \tag{1}$$

or $$\xi+\eta+n\lambda/2 = (\xi^2+r_n^2)^{1/2} + (\eta^2+r_n^2)^{1/2}. \tag{2}$$

The expansion of (2) gives

$$n\lambda = r_n^2\left(\frac{1}{\xi}+\frac{1}{\eta}\right) - \tfrac{1}{4}r_n^4\left(\frac{1}{\xi^3}+\frac{1}{\eta^3}\right) \pm \dots . \tag{3}$$

If one is only interested in aberrations up to the third order, one can use in the second term of (3) the approximation $r_n^2 = n\lambda f$ with $f^{-1} = \xi^{-1} + \eta^{-1}$. With $V = \xi/\eta$ one obtains

$$r_n^2 = n\lambda f + \frac{n^2\lambda^2}{4}\left\{\frac{V^3+1}{(V+1)^3}\right\}. \tag{4}$$

Up to now only zone plates with f-numbers of 50 to 100 in the soft X-ray region ($\lambda \lesssim 5$ nm) have been made holographically. At this point of development the third-order aberrations can be neglected. The only aberration of practical importance at this point of development is the spherical aberration which occurs by using zone plates with wavelengths different from the wavelength used for construction. This aberration can be corrected by using wavefronts with spherical aberration for constructing the zone plate. In the case that a zone plate is made with a spherical wave and a plane wave ($\eta \to \infty$) a variation of ξ has to be used in the following form [2]

$$\Delta\xi_n = \xi_1\left[1 - \left(1 - \frac{r_n^2}{\xi_1^2}\right)^{1/2}\right]. \qquad (5)$$

ξ_1 refers to the first zone, ξ_n to the nth zone with $\Delta\xi_n = \xi_1 - \xi_n$. The proper value of $\Delta\xi_n$ can be obtained by using r_n of eq. (4). Thus it is possible to make zone plates holographically for a desired wavelength, e.g., 4.4 nm, and a desired V.

For X-ray zone plates which are made with visible light the correction for example can be obtained with good approximation by using a plano-parallel plate P as shown in fig. 2.

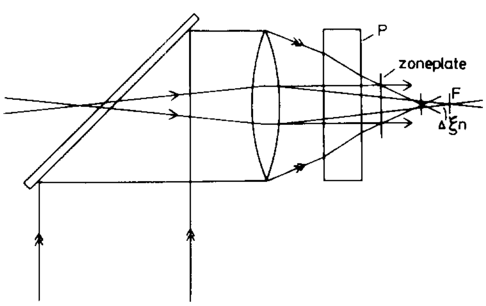

Fig. 2. Optical arrangement for the construction of zone plates with corrected spherical aberration.

3. Results

For microscopic purposes zone plates with the following parameters were made in our laboratory: r_n = 0.7 mm, r_1 = 17.4 μm ($f_{4.5\,\mathrm{nm}}$ = 68 mm), N = 1600. The zone plates are initially recorded in photoresist. Subsequent preparation yields a ring system in gold on a thin organic layer transparent to soft X-rays. To test such zone plates a strong X-ray source was developed [3] which was installed in a vacuum chamber.

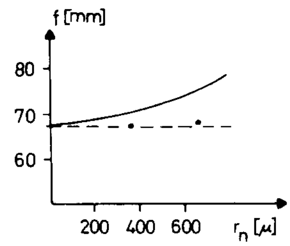

Fig. 3.

Fig. 3 shows the focal length of the above mentioned zone plate for the X-ray wavelength of CK_α (4.5 nm) as a function of r_n. The solid curve corresponds to the uncorrected zone plate if made with 457.9 nm. The points are measured values and show that these zone plates are well corrected concerning spherical aberration.

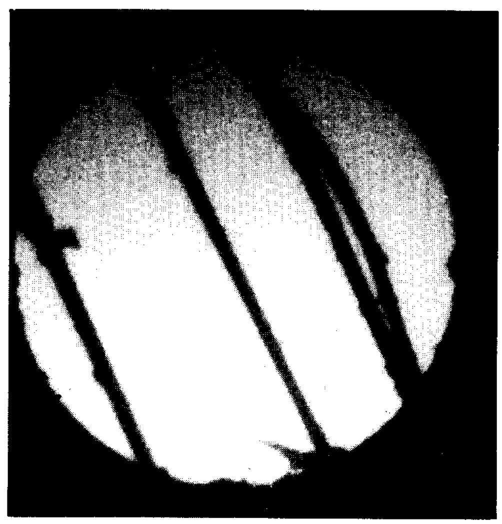

Fig. 4. Microscopic structures imaged with a zone plate using CK_α radiation (4.5 nm).

Fig. 4 shows a photo of microscopic structures made with CK_α radiation and a zone plate with the above mentioned parameters masked to a diameter of 1 mm and used in the first order. The photo shows wires with a diameter of 10 μm. The original enlargement was 10. The finest structures which can be resolved in this image are 2 μm. With monochromatic radiation the zoneplates used should be able to resolve structures of about 0.3 μm corresponding to the width of the outermost zones. That this value could not be obtained up to now is caused by the line width of the used CK_α radiation (compare fig. 6). According to eq. (4) f is approximately proportional to λ^{-1}. This yields a chromatic aberration disc proportional to $\Delta\lambda/\lambda$ with $\Delta\lambda$ equal to the width of the used X-ray line. To obtain the theoretical resolution a line has to be used with a value of $\Delta\lambda/\lambda$ about ten times smaller than the CK_α-line. It is therefore necessary to restrict the bandwidth.

4. Zone plates used as linear spectrometer

If a polychromatic parallel beam illuminates a zone plate at normal incidence, different wavelengths are focussed at different distances on the optical axis. Moving a counter combined with a small diaphragm along the optical axis yields a spectrum of the incident radiation.

Fig. 5 shows the arrangement of a zone plate spectrometer and the instrumental profile as a function of the diameter of the diaphragm. The intensity distribution near the focus along the optical axis for zone plates with large zone numbers is for monochromatic radiation proportional to a sinc-function. In this case calculations show that according to the Rayleigh criterion the spectral resolution is given by

$$R = \lambda/\Delta\lambda = N/2, \tag{6}$$

where $N/2$ = number of grating spacings. To get this resolution it is necessary to use a diaphragm with a diameter not larger than the diameter of the Airy disc [compare curve 1) in fig. 5].

In the case that the aperture of the diaphragm is large compared to the Airy disc, the instrumental profile is purely given by the geometric conditions and defines a volc-function

$$I = \begin{cases} \text{const.}, & \text{when } x \leqslant df/D\,; \\ x^{-2}, & \text{when } x > df/D. \end{cases} \tag{7}$$

In this case the spectral resolution is given by

$$R = \lambda/\Delta\lambda = r_n/d = D/2d. \tag{8}$$

A zone plate spectrometer was built to measure the line width of the CK_α-line which was used in our soft X-ray imaging experiments. The parameters of the used zone plate which originally was made for an astronomical rocket experiment to image the solar corona are: r_n = 2.5 mm, r_1 = 48.3 μm ($f_{4.5\,\text{nm}}$ = 52 cm), N = 2600. To measure the line width the X-ray source illuminated the zone plate through a pinhole of 30 μm diameter set up at a distance of $2f$. The measuring diaphragm was of the same size. This arrangement has an instrumental profile which is intermediate between the profiles 1) and 2) of fig. 5.

Fig. 6 shows the profile of the carbon line used, numerically corrected for the instrumental profile. The profile is in good agreement with measurements performed with grazing incidence spectrometers [4, 5]. From the results in fig. 6 it is obvious that a better spatial resolution when imaging microstructures with this line can only be received by restricting the bandwidth.

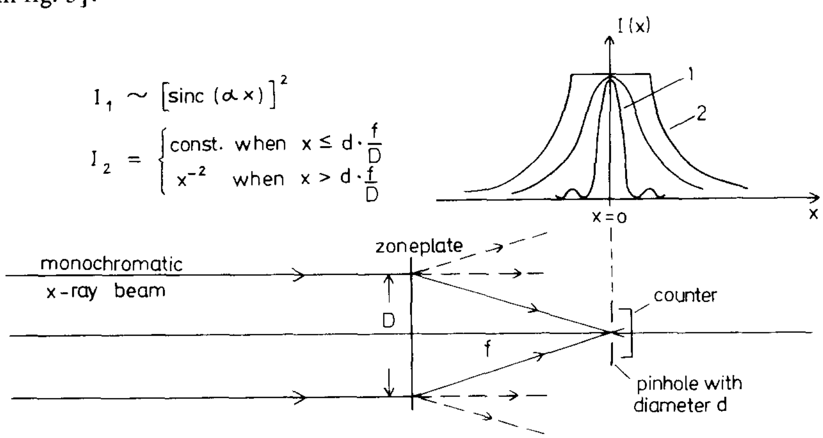

Fig. 5. Principle of a zone plate spectrometer.

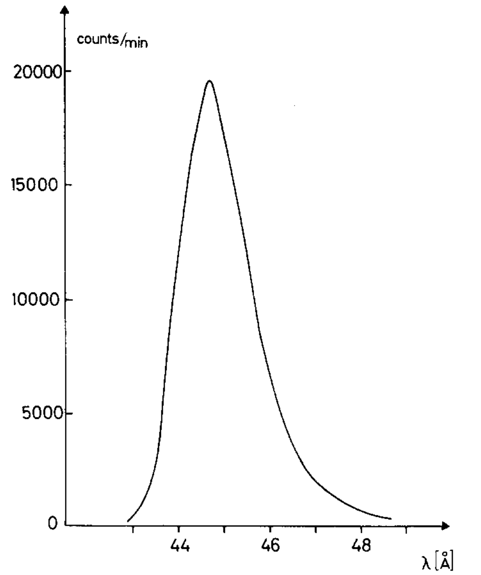

Fig. 6. CK_α-line profile measured with a zone plate spectrometer.

5. Conclusions

A zone plate spectrometer can be used as a monochromator. By adequate choice of the pinholes a small part of a broad line or of a continuum, e.g., synchrotron radiation, can be filtered. By using such a technique we hope to get the full resolution of holographically made zone plates.

Acknowledgement

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