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Résumé - Tous les procédés utilisés pour réaliser des lentilles à zone de Fresnel pour rayons X mous présentent des imperfections de fabrication qui affectent les images. On discute les erreurs possibles en microlithographie par microscopie électronique à balayage en transmission et on en conclut que ce procédé peut être utilisé en donnant une précision suffisante.

Abstract - Any process for making soft X-ray zone plates will have associated manufacturing errors which will affect the imaging properties. The errors possible in a lithographic manufacturing technique using a scanning transmission electron microscope are discussed, and it is concluded that sufficiently accurate zone plates may readily be made.

Introduction

Another contribution to these proceedings describes the manufacture of Fresnel zone plates, for use in soft X-ray microscopy, by a high resolution process using a STEM [1]. Manufacturing inaccuracies in this, and other, techniques lead to a reduction in the efficiency (which, in the first diffraction order of a perfect Fresnel zone plate, is $1/\pi^2$) and affect other imaging properties. Studies have been made of i) partial transmission through the absorbing zones and partial absorption in the transmitting zones; ii) displacements of whole or part zones; and iii) displacements of whole or part sectors. The calculations were carried out for 100 zones and an absorbing centre zone, although the results will be presented in a form, so far as possible, independent of the zone plate parameters. All the calculations were based on the Fresnel-Kirchoff diffraction integral for the image amplitude at an on-axis point. More detail is given in [2], where the effects of elliptical zones and stabilizing spokes are also discussed.

Since the effects considered do not move the major peaks of the diffraction pattern off-axis, how closely the imaging properties of an aberrated zone plate approach the ideal may be estimated using the Strehl ratio [3], i.e. the ratio of the peak intensity of the aberrated spread function (at a focus) to that of the equivalent perfect function. The tolerance limit is generally accepted to be when this has a value of 0.8 (the Strehl limit). When the zone boundaries are shifted or distorted, the focal lengths of the resulting zone plate are altered; in the results presented, refocussing has been carried out, where necessary, before calculating the Strehl ratio.

Incomplete Absorption or Transmission

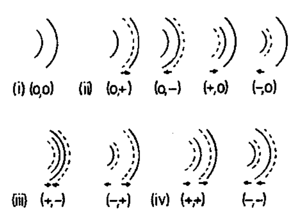
If γ is the fractional amplitude absorption in the absorbing zones (γ = 1 for complete absorption) then the diffraction pattern is not distorted but the intensity in a focus is reduced by a factor γ^2. Hence the focussed intensity is reduced while the background (unfocussed) radiation level is increased, leading to reduction in contrast. Alternatively, the focussed intensity could be enhanced if the radiation transmitted by the absorbing zones undergoes a phase change. Due to the lack of good measurements of soft X-ray optical constants, this is difficult to quantify.

Partial absorption in the transmitting zones is equivalent to inserting an attenuator in the beam so that less of the available radiation is focussed. However the image quality is not affected.

The first (uncoated) STEM generated zone plates have $\sim$ 0.15 µm of carbon in the absorbing zones (giving $\gamma^2 \simeq 0.75$ for a wavelength of $\sim$ 4 nm) and $\sim$ 20 nm of carbon in the transmitting zones (leading to an attenuation of $\sim$ 15%).

Displaced Zones

The displacements of zones may be characterised in terms of zone boundary shifts. For the case where the complete boundaries are displaced, each boundary may be left unshifted (o), moved inwards (−), or moved outwards (+). Expressing the boundary shifts in pairs, such as (+,−) which means that the odd-numbered boundaries are moved outwards and the even ones inwards, the situations indicated in figure 1 can be identified. These fall into 4 groups, (i) all zones left unchanged, (ii) every other boundary moved outwards or inwards resulting in the absorbing zones being too wide and the transmitting zones too narrow or vice-versa, with the zone centres displaced, (iii) successive boundaries moved in opposite directions, resulting in zones too wide or too narrow with undisplaced zone centres, and (iv) all zones moved outwards or inwards. The Strehl ratio for each of these groups is plotted against ε, the zone boundary displacement as a fraction of the outermost zone width in figure 2. The requirement for the on-axis intensity not to fall below the Strehl limit gives $\varepsilon < 0.21$



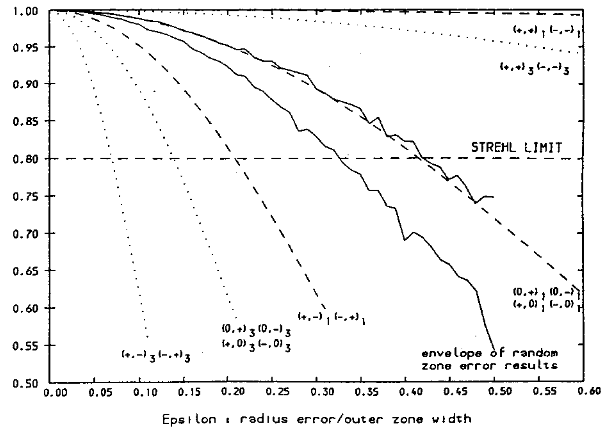


Fig. 1 - Dashed lines, correct positions. Full lines, actual positions of zone boundaries.

Fig.2 - Strehl ratios for displaced zones

for the worst case, (iii). Combinations of shifts involving more than two zones, e.g. (+,+,−), (+,o,−,+), give less stringent limits on ε. Zone plates made on the STEM will tend to have more random zone displacements - the envelope obtained from 100 separate computations in each of which the zone boundaries were displaced in random directions with random values of ε is also shown in figure 2. This gives the requirement $\varepsilon \lesssim 0.3$. The first zone plates made on the STEM have boundary positions correct to $\sim$ 5 nm with an outermost zone width of $\sim$75 nm, i.e. $\varepsilon \sim 0.07$ giving a Strehl ratio of $\sim$ 0.99 for first order imaging. For higher order foci, which can in principle give better resolutions, the Strehl limit is reached for smaller values of ε, i.e. the manufacturing tolerances are stricter. This is shown for the third order focus in figure 2.

In the STEM manufacturing method, the zone plate patterns are drawn in 24 equal angular sectors, misalignments of which could result in discontinuities (steps) in the zone boundaries. Possible configurations of steps are shown in figure 3, and the resulting Strehl ratios in figure 4 - these calculations were carried out assuming that

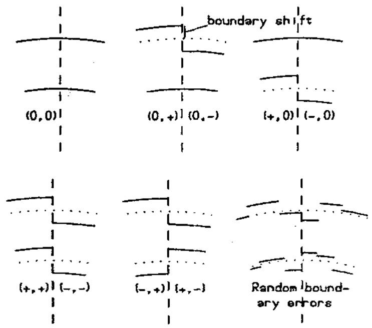


Fig. 3 - Stepped zone boundaries.

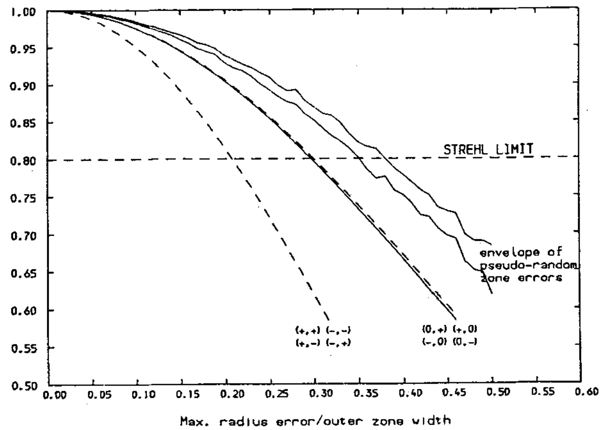


Fig. 4 - Strehl ratios for stepped zone boundaries.

the configurations shown are repeated every two sectors. For the worst case, $\varepsilon < 0.21$; groups of more than two sectors give less stringent limits. For random step positions and sizes (see figure 3 - this could happen if, for example, the STEM stage drifted between registrations), the envelope shown in figure 4 is obtained, giving $\varepsilon \lesssim 0.35$. For a step size of ~ 5 nm and a ~ 75 nm outermost zone width, the Strehl ratio is ~ 0.99.

Since each sector of the zone plate on the STEM is drawn as three fields [1], a possible (perhaps the most likely) combination of displaced zones is that a whole (or part) field is drawn in the incorrect place. This could happen if, for example, a registration mark is partly obscured by an imperfection in the film. If one field (of the whole zone plate) is displaced, the resulting Strehl ratio, as a function of ε, is shown in figure 5. Displacement of an outer field (i.e. of an outer part of the zone plate) has a larger effect than displacements of a middle or inner field, due to the larger area. Figure 5 also shows the effect of displacing more than one

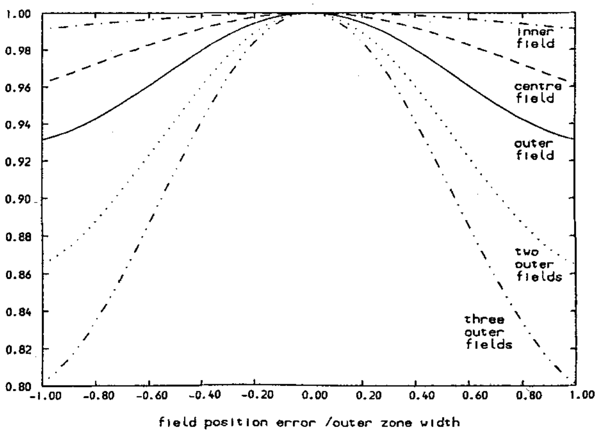


Fig. 5 - Strehl ratios for displaced fields.

outer field. For field displacements of ~ 5 nm, the Strehl ratio remains well above the Strehl limit. The field positions can be monitored visually throughout the manufacturing process, and so any gross errors can be detected and, if necessary, the process restarted.

Conclusions

Of the effects considered, the major degradation in focussed intensity arises from incomplete absorption and transmission in the absorbing and transmitting zones respectively. The other effects cause very small decreases in the focussed intensity. Although they have been considered separately above, the various effects will all contribute to varying extents, but the accuracy of the manufacturing process is such that the Strehl ratio should always be well above the limit of 0.8 for STEM generated zone plates.

Acknowledgements

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References

[1] BROWNE M.T., CHARALAMBOUS A., BURGE R.E., DUKE P.J., MICHETTE A.G. and SIMPSON M.J., these proceedings p.

[2] SIMPSON M.J. and MICHETTE A.G., to be published in Optica Acta (1983).

[3] WELFORD W.T., in "Aberrations of the Symmetrical Optical System", p.206, Academic Press (1974).