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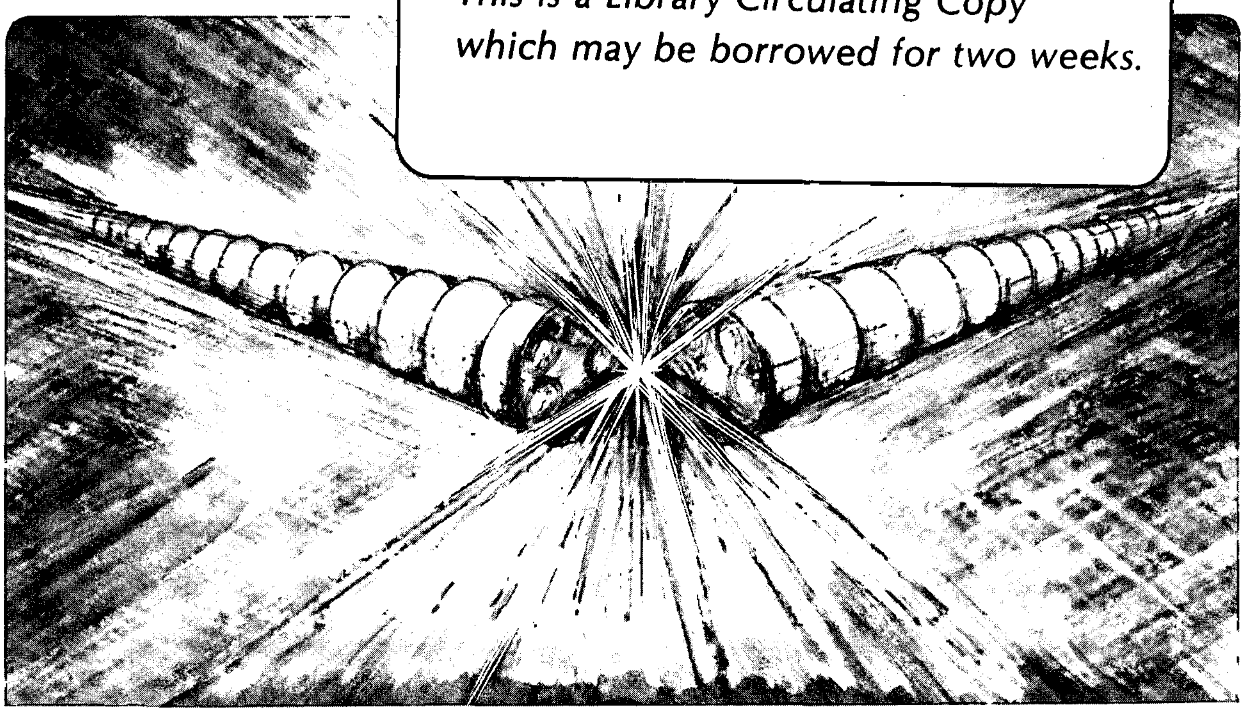

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DESIGN OF GRAZING INCIDENCE MONOCHROMATORS INVOLVING UNCONVENTIONAL GRATINGS

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1. Introduction

The manufacture of varied line space (VLS) gratings was pioneered by Harada and co-workers of Japan,[1] and Gerasimov and co-workers in the Soviet Union.[2] Ruling engines were modified to allow the groove spacing to vary in a continuous manner, the grooves often remaining straight and parallel. This type of grating can also be obtained in the United States from Perkin Elmer Co. of Irvine, CA. Other VLS gratings involving fan shaped or concentric grooves have been developed by these groups and Hyperfine, Inc. of Boulder, CO. Monochromators using VLS for the UV and higher energy regions have been developed by Hettrick.[3] We review the basic aspects of second order focusing of straight and parallel grooved varied line space gratings in both converging and collimated light in a more explicit and detailed manner that we have found in the literature. The effects of the VLS correction to the location of the focal curve for grazing incidence geometries are found to be very significant.

2. Geometry

We consider two cases shown in Fig. 1a and 1b. The light can be converging to a focal point behind a VLS grating as in Fig. 1a, or impinging onto the grating as a parallel beam as in Fig. 1b. The grating is assumed to be a plane or have a relatively long radius of curvature.

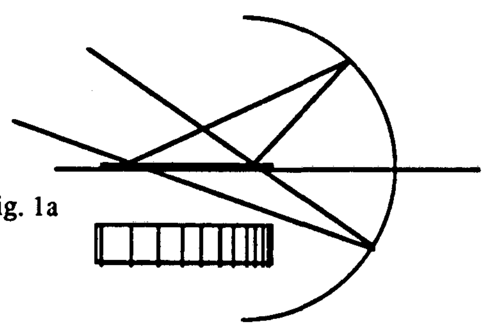

Fig. 1a

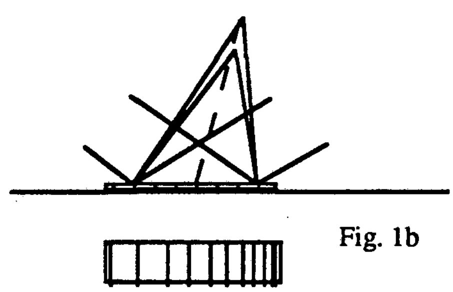

Fig. 1b

We adopt the familiar coordinate system and optical path function analysis of Noda, et al.[4] which is shown in Fig. 2. The path function is written as the difference between the path taken by a general ray and the pole ray plus a term which accounts

$$\Psi = \langle APB \rangle - \langle AOB \rangle + Nm\lambda \qquad 2.1$$

for the presence of the grating grooves. We then choose to expand the groove spacing about the spacing at the center of the grating, d_0.

$$d = d_0\left[1 + \mu y + \nu y^2 + \kappa y^3 + \ldots\right] \qquad 2.2$$

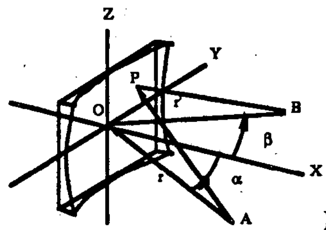

Fig. 2

Here d, the groove spacing as a function of distance along the grating width y, is equal to the partial derivative of y with respect to the groove number N. The defocus coefficient, F_{20}, can now be found by taking the second derivative of Ψ with respect to y, and evaluating at y = z = 0:

$$\left.\frac{\partial^2\Psi}{\partial y^2}\right|_0 \equiv F_{20} = M_{20} + \left.\frac{\partial^2 N}{\partial y^2}\right|_0 m\lambda \qquad = M_{20} + \left[\frac{\delta}{\delta y}\left(\frac{\delta N}{\delta y}\right)\right]_0 m\lambda = M_{20} + \left[\frac{\delta}{\delta y}\left(\frac{1}{d}\right)\right]_0 m\lambda$$

$$= M_{20} + \left[\frac{\delta}{\delta y}\left(\frac{\delta N}{\delta y}\right)\right]_0 m\lambda = M_{20} + \left[\frac{\delta}{\delta y}\left(\frac{1}{d}\right)\right]_0 m\lambda \qquad = M_{20} + \left[\frac{\delta}{\delta y}\left(\frac{1}{d_0\left(1 + \mu y + \nu y^2 + \kappa y^3 + \ldots\right)}\right)\right]_0 m\lambda$$

$$\Rightarrow F_{20} = M_{20} - \frac{\mu m\lambda}{d_0} = M_{20} - \mu(\sin\alpha + \sin\beta)$$

2.3

We have used the grating equation to arrive at the last equation. M_{20} represents the classical terms which are not associated with the VLS correction. Inserting these, where a_{20} depends on the shape of the grating, gives.

$$F_{20} = \frac{\cos^2\alpha}{r} + \frac{\cos^2\beta}{r'} - 2\,a_{20}(\cos\alpha + \cos\beta) - \mu\,(\sin\alpha + \sin\beta) \qquad 2.4$$

We include without derivation the equivalent expressions for the coma and spherical aberration coefficients.

$$F_{30} = M_{30} + \frac{2m\lambda}{d_0}\left(\mu^2 - \nu\right) = M_{20} + 2\left(\mu^2 - \nu\right)(\sin\alpha + \sin\beta)) \qquad 2.5$$

$$F_{40} = M_{40} - \frac{6m\lambda}{d_0}\left(\mu^3 - 2\mu\nu + \kappa\right)$$
$$= M_{40} - 6\left(\mu^3 - 2\mu\nu + \kappa\right)(\sin\alpha + \sin\beta)) \qquad 2.6$$

3. Standard Case

Our test case for evaluating the conditions of defocus is the following:

fixed deviation monochromator, half deviation angle = 87 degrees
order of diffraction = +1 (inner order, $|\beta| < \alpha$)
wavelength range = 20 A to 40 A
focus of the converging incident light 1 meter behind the grating
grooves per mm = 1200 at the center of the grating

Following Hettrick,[5] we set F_{20}=0 at the two extrema of the wavelength range, 20 A and 40 A. These two equations can be solved for the ratio of the distance to horizontal focus from the grating pole r_H' to the distance to the object point from the grating pole r_H, where we define r_H as positive behind the grating, and insert a minus sign into each equation to compensate.

$$\frac{r_H'}{r_H} = \frac{\lambda_1 \cos^2\beta_2 - \lambda_2 \cos^2\beta_1}{\lambda_1 \cos^2\alpha_2 - \lambda_2 \cos^2\alpha_1} \qquad 3.1$$

For our case r_H'/r_H = 1.00448. Either of the individual equations can be solved for μ to give μ = +1.986225. This effectively puts the two available zeros of the defocus coefficient at the two chosen wavelengths. This coefficient is shown in Fig. 3.

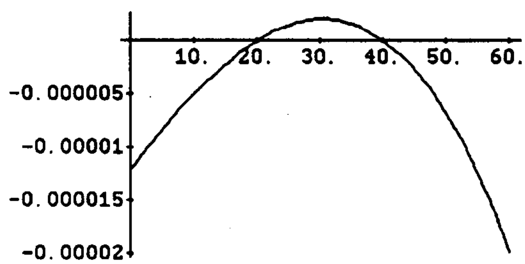

Fig. 3

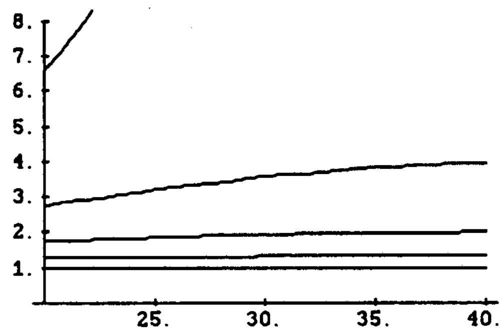

Fig.4

The effect of this remarkably low defocus is shown in Fig. 4. Here the value of r_H'/r_H is plotted for zero, 25, 50, 75 and 100% of μ = +1.986225. We see that the distance to horizontal focus varies greatly for the μ = 0 case (no VLS). For full correction, the distance to focus is essentially flat on any scale that shows the case with μ = 0. If we define a "variance" for r_H' as a quantitative measure of its deviation from perfect focal correction, and rationalize to the lowest value to guarantee that we will count only "flatness"; then the correction is seen to be quite dramatic in Fig. 5. The $\log_{10}$ of the "variance" or merit function M, defined below, is plotted as a function of μ.

$$M = \sum_{\lambda_1}^{\lambda_2} \left[\frac{r_H'(\lambda)}{\min\{abs[r_H'(\lambda)]\}} - \frac{r_H'(\lambda)}{\min\{abs[r_H'(\lambda)]\}} \right]^2$$

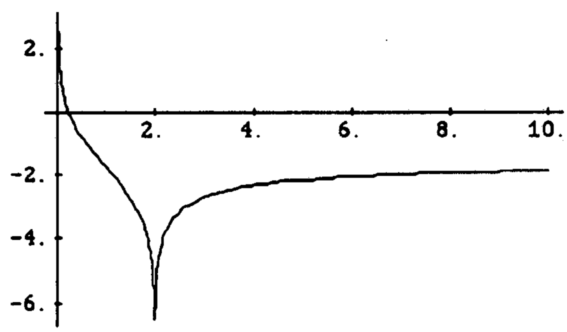

Fig. 5

Since in Fig. 4 we plot r_H'/r_H with r_H at the standard value of 1, we can see that at least for our standard case the optimal VLS correction to this order occurs naturally near the point where the light would focus without the grating. This is very fortunate, since in the sagittal direction the straight grooved grating does not affect the focusing at all. We have varied the parameters of the standard case and find that the best flattening of the horizontal focal curve does in general occur near unity magnification for the grating. This does not occur when the VLS grating is used to focus parallel light. Letting $r_H \to \infty$ in equation 2.4 (a_{20}=0) and solving for r_H' gives,

$$r_H' = \frac{d \cos^2(\beta)}{\mu\, m\, \lambda} \qquad 3.3$$

showing that μ is just a scaling factor which determines the distance to the tangential focus. The shape of the focal curve does not change as does the case of converging light. Changing μ moves the curve in and out, but does not "flatten" the curve, which is shown in Fig. 6 which plots r_H'/r_H as a function of wavelength for r_H =1.

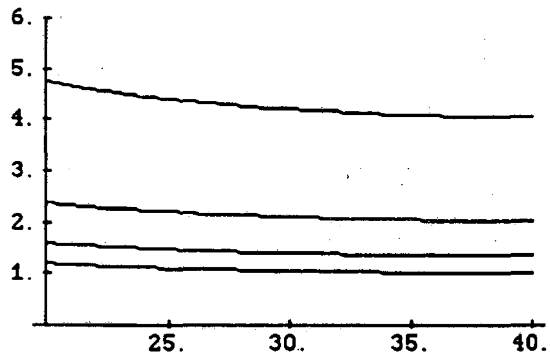

Fig. 6

We see that the focal curve correction is not nearly as good as when the VLS grating is used in converging light. However for moderate resolution instruments for synchrotron radiation beam lines where the radiation can have very low divergence, the VLS grating in collimated light can be used to advantage. If the grating can be translated as it is rotated, as has been reported by Itou et al.[6], the small defect of focus can be compensated.

4. Summary.

We have shown the following:

1. Plane VLS gratings provide profound focal curve correction when used at grazing incidence and in converging light.

2. Moderate resolving power instruments are possible using collimated light.

3. Optimal VLS linear spacing variations naturally give a tangential focal distance near the sagittal focus for cases similar to these in converging light.

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