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MASTER

DESIGN OF X-RAY MICROSCOPES FOR LASER-FUSION APPLICATIONS*

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Abstract

Design techniques for Wolter grazing incidence x-ray microscopes are discussed, and considerations applicable to diamond point micro-machining fabrication are described. Also preliminary results of tests on a micro-machined mandrel replicated system are presented.

Introduction

The design of grazing incidence x-ray microscopes has been discussed by Kirkpatrick and Baez⁽¹⁾ and by Wolter.⁽²⁾ Microscopes of the Kirkpatrick type have been used for laser-produced plasma measurements,⁽³⁾ but, although a microscope of this type is easy to fabricate, the aperture must be quite small to obtain good resolution. The most common microscope for laser target measurements is a simple pinhole camera which uses a 5 μm pinhole to provide a resolution of approximately 5 μm with a solid angle of 3.5×10^{-7} sr, similar to that of the Kirkpatrick instrument. Both the Kirkpatrick microscope and the pinhole camera produce acceptable time-integrated exposures in current experiments, but the resolution is inadequate for future experiments, and the sensitivity is marginal for time-resolved measurements. The Wolter microscope, then, offers the best possibility for obtaining resolution approaching 1 μm with an aperture exceeding that of a pinhole camera by a factor of 100 or more. A particular system of this type has been proposed by Chase and Silk,⁽⁴⁾ but this discussion will be devoted to the general characteristics of Wolter systems and the applicability of diamond-point turning techniques to their fabrication.

Wolter showed analytically that grazing incidence, confocal hyperboloid-paraboloid systems which satisfy the Abbe sine condition at their intersection point are free of aberration for object points sufficiently close to the axis. For finite conjugates the confocal hyperboloid-ellipsoid system satisfies the Wolter criteria. It will be shown that the Abbe condition is not a strong constraint because microscope performance is limited by fabrication errors rather than aberrations.

Ray Tracing Principles

The equations of the surfaces of a Wolter system can be written as:

$$(z-k)^2/a^2 + (x^2+y^2)/b^2 = 1 \quad (1)$$

for the ellipsoid and

$$z^2/c^2 + (x^2+y^2)/d^2 = 1 \quad (2)$$

for the hyperboloid. Imposing the confocal condition gives

$$k = (a^2-b^2)^{1/2} - (c^2+d^2)^{1/2} \quad (3)$$

Other forms of these equations can be written⁵ to emphasize the relation to physical parameters such as focal length and magnification, but this form of the equations is efficient for numerical ray tracing. As a design tool it is more convenient to use a simple computer code to determine a, b, c, and d, which are then used as input parameters for a ray-tracing program.

In general, approximate relationships derived from Eq. (1), (2), and (3) are too crude to be of use for accurate design. The physical characteristics of importance for the use and design of a microscope are the magnification, M, the grazing angle, θ_g , the radius at the ellipsoid-hyperboloid intersection, R, and the object distance, d_o . The image distance, d_i , is, then, given by

$$d_i = M d_o \quad (4)$$

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A set of nonlinear algebraic equations can be derived easily by equating Eq. (1) and (2) at the intersection surface, z_i , to determine R , and observing that a ray vector, R_1 , which strikes the hyperboloid at the intersection has an angle of incidence given by

$$\cos\theta_i = \vec{R}_1 \cdot \vec{n}_H / |\vec{R}_1| |\vec{n}_H| \quad (5)$$

where

$$\theta_i = \pi/2 - \theta_g \quad (6)$$

and \vec{n}_H is the normal to the hyperboloid surface.

These equations can be solved self-consistently for a , b , c , and d . Since the x-ray reflectivity is determined by θ_g , the magnification is determined by detector resolution, and the image distance is determined by experimental conditions or surface errors, specifying the radius and imposing the Abbe condition over-determines the system. It is desirable to make the radius as large as possible to make fabrication easier, and, thus, it is frequently necessary to violate the Abbe condition. It has been found that differences of 20 percent in the angles of incidence at the hyperboloid and the ellipsoid are of no consequence for laser-fusion applications.

To serve as an effective design aid, a numerical ray tracing computer program must be fast, interactive, and simple to use. Generalized ray-tracing codes are cumbersome to use, costly in computer time and unnecessary for this application. A Monte-Carlo code has been written for the CDC 7600 which generates random rays with a $\cos\theta$ distribution, which is truncated to slightly overfill the aperture of the optical system. Intersections of rays with surface are solved exactly from the ray equation and Eq. (1) or Eq. (2), and reflected rays are calculated by observing that, for \vec{n} the unit vector normal to the surface, R_1 the unit incident ray vector, and R_2 the unit reflected ray vector, at the reflection point

$$\vec{R}_1 \cdot \vec{n} = -\vec{R}_2 \cdot \vec{n} \quad (7)$$

$$\vec{R}_1 \times \vec{n} = \vec{R}_2 \times \vec{n} \quad (8)$$

These equations can then be solved for \vec{R}_2 . Although a closed form solution is possible to obtain, the code solves the linear system directly to provide flexibility in including slope errors. Because Eq. (7) and (8) determine the cosine and sine, respectively, of the angles of incidence and reflection, a slope error can be included as a perturbation by adding a small error to the reflected angle. The code requires approximately one second of computer time for tracing 100 rays, including errors in slope and radius, stop intersections, wavelength and angle dependence of reflectivity, and graphical and printed output.

Surface Errors

The problem of determining errors for these systems has not been completely solved. Silk⁽⁶⁾ has measured the spread in scattering angles from a micro-machined flat to be approximately 60 μ rad, but there is no assurance that this value can be attained for figured surfaces. Scatter measurements have been made for x-ray telescopes,⁽⁵⁾ but the figure requirements are somewhat different for microscopes, and optical testing is difficult for these smaller systems. For an average slope error, $\Delta\theta$, it is found that the resolution, r , is, approximately,

$$r = f_0 \Delta\theta. \quad (9)$$

Using Silk's scatter result, one can see that micro-machined surfaces limit f_0 to, approximately, 3 cm for 2 μ m resolution. To avoid shadowing of the surface by tool marks the grazing angle should be made as large as possible, and 1.7 degrees is a reasonable compromise. Using these parameters a system can be designed which has a field of view of $\pm 100 \mu$ m. Sinusoidal errors have been observed in micromachined surfaces,⁽⁷⁾ and the ray tracing code treats these by using the derivative to calculate a slope error. For a sinusoidal surface variation with axial symmetry given by

$$\Delta R = A \sin(2\pi z/\lambda + \phi) \quad (10)$$

where λ is the wavelength of the perturbation, and ϕ is a phase, which can be constant or random, the slope error is given by

$$\Delta\theta \approx \tan\theta = (2\pi/\lambda) \cos(2\pi z/\lambda + \phi). \quad (11)$$

The resolution is, again, given by the product of object distance and slope error, and this error, approximately, adds in quadrature with the gaussian error described above. For a wavelength of 1 nm an amplitude of 100 Å or less is required for 1 μm resolution in a system having an object distance of 2 cm. It should be observed that these tolerances are inversely proportional to object distance, and for distances as large as 30 cm it is not clear that even the best hand finishing and testing techniques will be adequate to achieve 1 μm resolution.

In the ray tracing calculations it is assumed that all slope errors deflect the rays only in the plane of incidence. Because of the small grazing angles used, this assumption should be well satisfied.

Alignment Tolerance

The alignment of a Wolter system can be rather difficult. The field of view transverse to the axis of symmetry is, typically, 200 μm or more, and, thus, although the alignment accuracy must be ~ 10-20 μm, this accuracy has been routinely attained in current laser-fusion experiments. In general, the pointing accuracy must be 30-50 μrad independent of focal length. An accurate starting point can be found by observing visible light point source images from the hyperboloid and ellipsoid at a point out of the focal plane, where the surfaces form rings of the same diameter. The source lies on the axis when the circles are concentric. Micro-machining the entire microscope reduces the difficulty of this operation because the surfaces are known to be coaxial.

The major problem in the alignment and use of the Wolter system, however, is the limited depth of field. Simple geometric arguments show that the depth of field, Δz, of a microscope is given by

$$\Delta z = \frac{r}{2(\theta_{g1}^2 + \theta_{g2}^2)} \quad (12)$$

where r is the resolution and θ_{g1} and θ_{g2} are the grazing angles at the two surfaces. For grazing angles of 1.5 degrees and a resolution of 1 μm, for example, the depth of field is approximately 10 μm, and a positioning error less than ~ 5 μm is required. This requirement is not absolute, however, but it is a constraint on the reproducibility of target alignment. If the target is displaced by 100 μm, for example, in a particular case, and if the detector is repositioned for optimum focus, neither the field of view nor the resolution changes. The grazing angle does change, and the effect on the reflectivity must be considered. For calibrated operation at photon energies such that the grazing angle is near the critical angle accurate alignment is required.

Design Example

Using the principles described above a particular system was designed. Beginning with an object distance of 3.2 cm and a magnification of 10, the radius of the intersection surface was increased until the grazing angle at the hyperboloid reached 1.8 degrees. The radius was 3.44 mm, a value large enough for fabrication by micro-machining. A section of the reflecting surfaces of the optical system is shown in Figure 1. The projection of the hyperboloid on the z-axis is 5 mm, and all rays from the hyperboloid strike the ellipsoid. The ellipsoid projection is 5.8 mm. The surfaces appear as straight lines because the sagittal depth is approximately 1 μm. Figure 2 shows the ray pattern at the image plane for a point source 50 μm off axis, and Figure 3 shows a simulated densitometer scan of the image. Note that the maximum occurs at 247 μm rather than 250 μm (M = 10). This and the skewed image in the displacement direction are in agreement with Wolter. When a gaussian random error of 60 μrad was included, the densitometer trace of Figure 4 was calculated. The sharp central spike has a FWHM of 1 μm (at the source), but the radius of the circle containing half the energy is approximately 3 μm. This characteristic of these systems tends to produce low accutance images even though point source measurements give sharp images. The parameters of Eq. (4) and Eq. (2) for this system are

$$\begin{aligned} a &= 19.78 \text{ cm} \\ b &= 0.4464 \text{ cm} \\ c &= 1.973 \text{ cm} \\ d &= 0.1400 \text{ cm} \end{aligned} \quad (13)$$

The geometric solid angle is 3.6×10^{-3} sr, but the effective aperture for 6.18 Å x-rays is, approximately, a factor of 4 smaller.

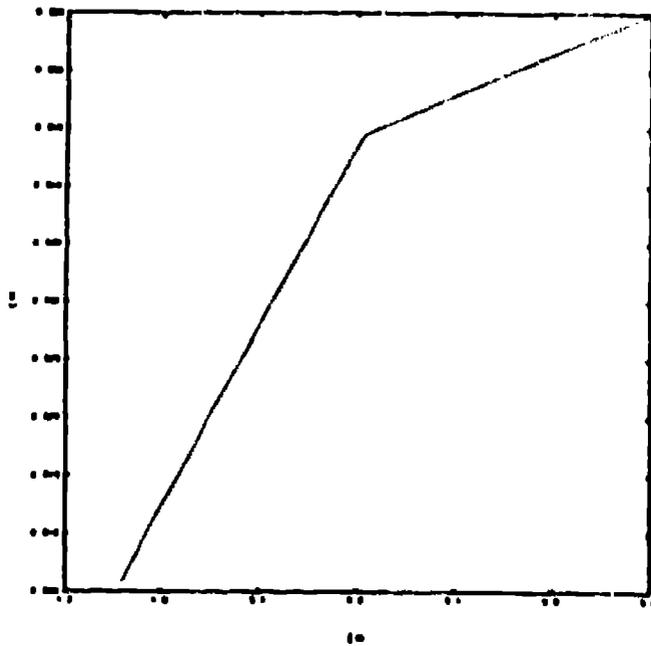


Fig. 1. Section of reflecting surfaces of an x-ray microscope.

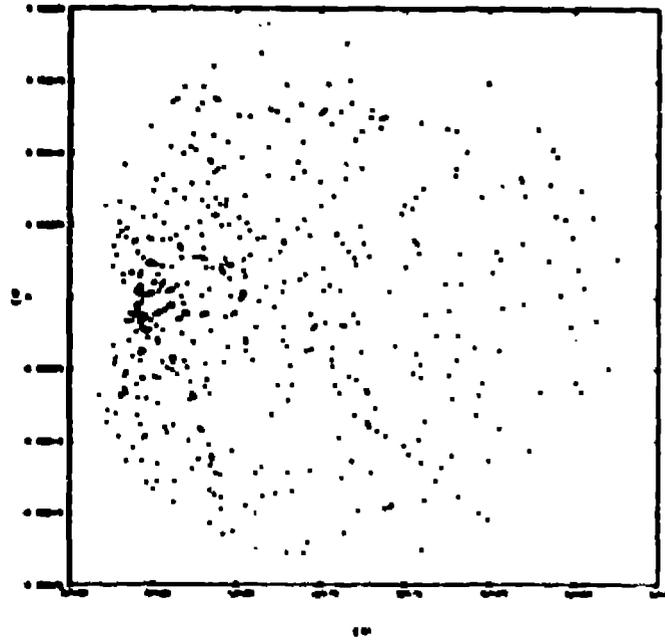


Fig. 2. Image plane ray pattern of a point source 50 μm off axis.

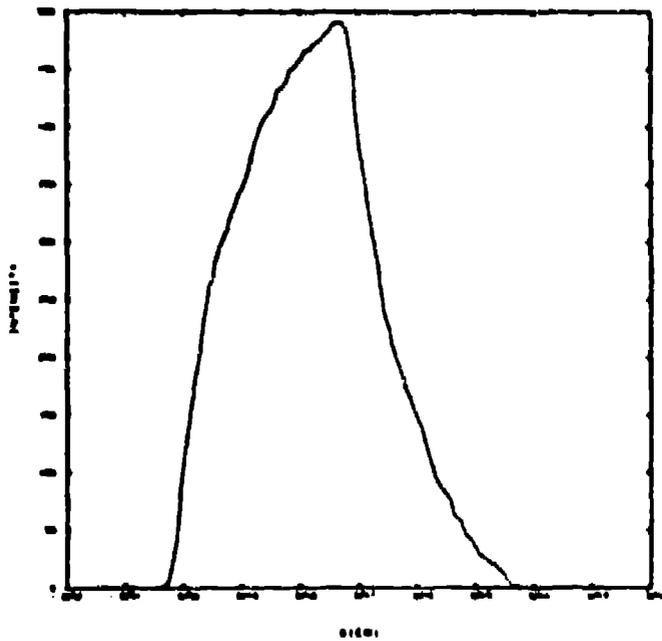


Fig. 3. Simulated densitometer trace of the ray pattern of Fig. 2.

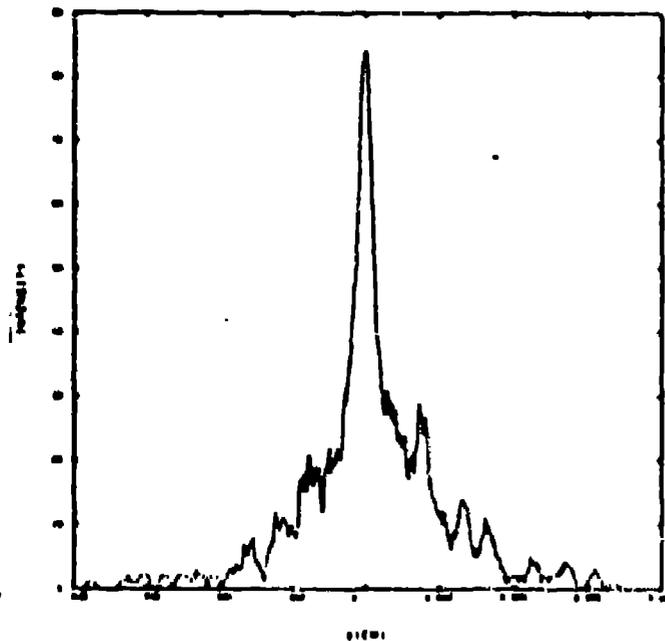


Fig. 4. Densitometer trace of the arrangement of Fig. 2 with a 60 μrad random error.

Fabrication

The system described above was fabricated at Union Carbide's Y-12 plant, Oak Ridge, Tennessee. It was suggested by P. Steyer that a mandrel be machined of aluminum and that nickel be electroplated on the mandrel. The mandrel could then be dissolved by NaOH. It was found by J. Arnold, however, that the mandrel could be extracted easily by cooling the assembly 20-30°C below room temperature. The completed mirror is shown in Figure 5.

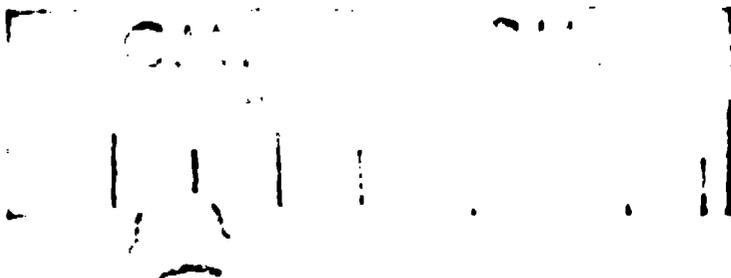


Fig. 5. Micro-machined and replicated x-ray microscope. Material is electro-plated nickel.



Fig. 6. Image of USAF resolution chart (12.7 lp/mm) produced in white light by the system of Fig. 5.

Testing

No x-ray measurements have been done because of the recent completion of the fabrication. Tests have been performed using visible light sources, however, and a white light image of a standard USAF resolution chart is shown in Fig. 6. The closest spaced lines correspond to 12.7 lp/mm. These and monochromatic point source measurements indicate that the system is diffraction limited in the visible region and that no gross fabrication errors exist. The x-ray performance cannot be predicted from this result, and x-ray measurements are in progress.

Conclusions

It has been shown that efficient computer design tools, which allow rapid and effective design of Wolter systems, can be constructed, and that such systems can be fabricated by micro-machining techniques. The x-ray response of these systems remains to be determined although visible light tests are encouraging. It should be noted that even if hand polishing is required, machining of these surfaces will probably be cost effective because the cost of the system described was approximately one percent of the cost of a hand-figured system.

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