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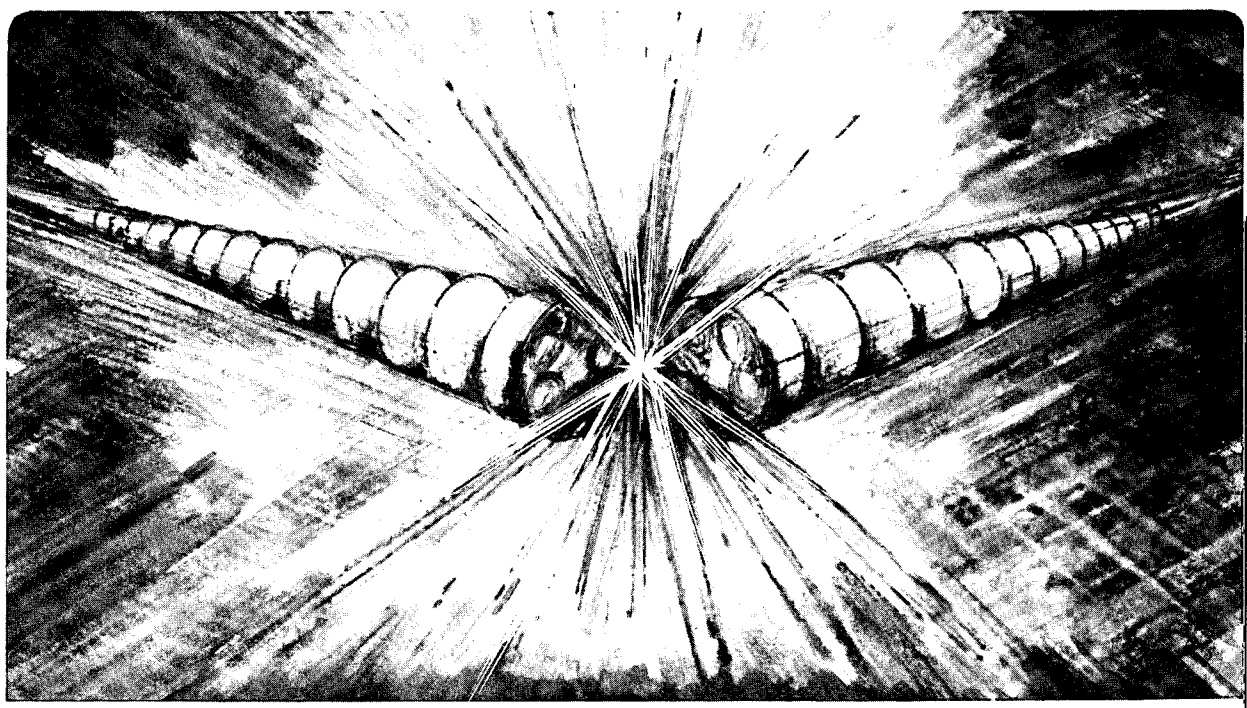

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ABSTRACT

The performance of multilayer-coated Schwarzschild objectives, and similar near normal incidence soft x-ray focussing systems, can be affected by the changing angles of incidence for different rays and possible variations in multilayer period across the curved mirror surfaces. A design analysis which considers these issues is presented, using as an example a 20 times demagnifying Schwarzschild objective coated with molybdenum/silicon multilayers for operation at roughly 76 eV. The large bandwidth of these multilayers eases requirements on control of the variation of the d-spacing for the system considered. Implications for extension to similar systems operating with different magnifications, sizes, and photon energies are discussed.

1. INTRODUCTION

The advent of multilayer reflective coatings for extreme ultraviolet to x-ray (XUV) wavelengths in the last decade has extended the spectral range of significant near-normal incidence reflectance into these regions. Especially exciting among the many applications made possible by these nanometer-scale interference structures are those in which multilayers are applied to curved optics for focussing. Such applications include, for example, experiments utilizing a single curved multilayer mirror for imaging[1,2,3] and for gain enhancement in multipass x-ray laser experiments.[4,5] Compound multilayer-coated focusing optics, such as Schwarzschild objectives, are beginning to be utilized in microscopy[6,7,8,9] and astronomy, and these and similar optics are being investigated for use in soft x-ray projection lithography.[10,11,12] It is this later class of compound multilayer-coated, near-normal incidence optics that are the subject of this paper.

This paper investigates issues relating the areal distribution of multilayer period on the curved surfaces of compound reflective optics to the performance of these optics. We present an analysis combining the geometrical optical considerations of Schwarzschild objectives with the physical optical considerations relating to multilayer reflective structures and the deposition system dependent considerations which affect the variation of multilayer period on curved surfaces. Discussion is based on experience gained in the course of the design and coating of several different Schwarzschild objectives (SO) for soft x-ray magnifying and demagnifying applications. To illustrate the analysis we examine a 20X reduction system which demagnifies a beam from an undulator source at the Synchrotron Radiation Center (University of Wisconsin, Madison) to form a sub-micron spot primarily for use in photoelectron spectro-microscopy studies of various surfaces. Some details this project, called MAXIMUM, can be found in ref. 8.

2. THE PROBLEM

The essential features of concern here can be appreciated by considering the path of a single ray through the SO in Fig. 1, and by remembering that multilayers are specular reflectors which also obey the interference condition commonly known as Bragg's law. The Bragg equation, $\lambda = 2d\cos(\theta)$, relates the reflected x-ray wavelength λ to the local multilayer period d (assumed corrected for refraction) and the local angle of incidence (from normal) θ. For the multilayers considered here Bragg's law is relaxed to let a relatively large band of wavelengths reflect because a relatively small number of multilayer periods contribute to the interference. For simplicity we assume incident radiation with a narrow λ distribution compared to the large multilayer bandpass is incident on the SO. A single ray has a different θ at each mirror, so that an optimal design would have different multilayer periods for that ray at the primary and secondary mirrors. Likewise different rays make different angles on the same mirror, implying that multilayer periods should vary across each mirror. Thus, geometrical optics determines the optimal variation of multilayer period d over the clear aperture of each mirror as that which satisfies the Bragg equation for fixed λ. But this is only part of the problem.

A second set of concerns arises from realizing that depositing multilayers onto the curved surfaces of the primary and secondary mirrors in general results in a variation of multilayer period d across each mirror. The obtained variation in d across the optical surfaces will not generally be the optimal variation mentioned above. In practice the actual variation can be controlled to some extent. This requires a measurement or other determination of the variation in d before a method for controlling that variation can be implemented.

The relatively large effort required to obtain the actual variation in d across curved optics, and then to implement and verify means to optimize that variation, has to date lead us to adopt a simplified approach. This approach is to predict the variation in period over these curved surfaces expected in our sputter deposition system, and then to determine whether this variation is acceptable for the application at hand.

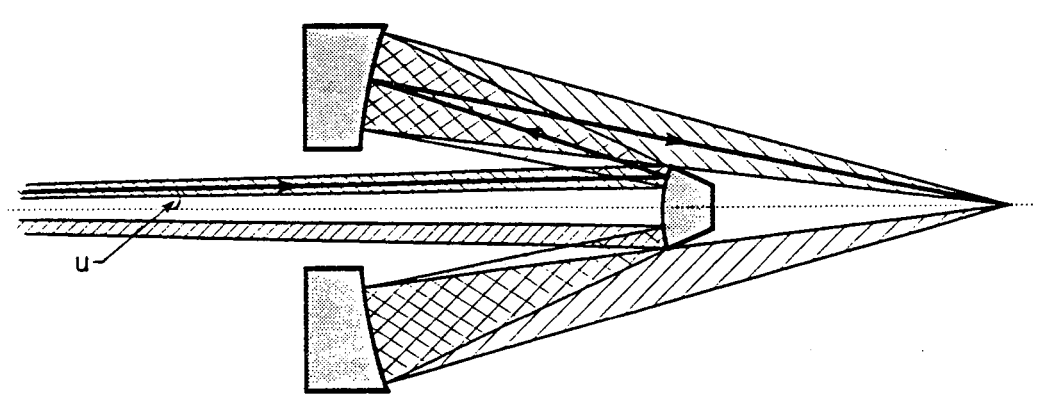

Fig. 1. Cross section including the optic axis of a 20 times demagnifying Schwarzschild objective. The smaller mirror is the primary, and the larger the secondary mirror. The cross-hatched regions include the set of rays which pass through the clear aperture of the system, and the initial off-axis angle U is indicated.

3. ANALYSIS

Geometrical ray-tracing to follow rays through the clear aperture of the Schwarzschild objective is combined with predicted variations in multilayer period across the two mirrors based on characterization of our multilayer deposition system. For the application of the SO under consideration here, a grating monochromator upstream of the SO provides an incident beam with high energy resolution compared to the bandwidth of the multilayer.

3.1. Criteria for assessing acceptable multilayer period variation

Before proceeding with this analysis we consider how to determine what variation of multilayer period across the two mirrors is acceptable. Figure 2(a) shows a calculated reflectance vs. hν for a Mo/Si multilayer having 20 periods each of 88.4 Å and with $\theta = 8.0°$. The bandwidth of this peak, $\Delta h\nu/h\nu = 0.076$, provides one scale for this purpose. For instance, one criterion could be that variations in d which shift the multilayer Bragg peak in Fig. 2(a) by less than some fraction of the FWHM are acceptable, since there would still be significant multilayer reflectance for all such cases. Choosing half of the FWHM would then yield an acceptable range of variations in d of 3-4% for this case.

A second criterion is based on the knowledge that the phase shift on reflection from a multilayer changes rapidly across the multilayer Bragg peak, as shown in Fig. 2(b). This differing phase change across the Bragg peak may become important assuming that the figure of the mirrors and SO alignment are perfect enough so that differences in the optical paths of different rays introduce phase errors less than π. Then a variation of multilayer period would cause different rays to experience different phase changes on reflection even if all rays reflect from within the Bragg peak region. This dispersion in phase change would have implications for diffraction-limited imaging, effectively blurring the focal spot. This second criterion would require that the dispersion in phase change on reflection for all rays be less than some fraction of π. This fraction could be 1/2, 1/4 or less, and could be determined by image simulation calculations. In Fig. 2(b) we see that the phase change on

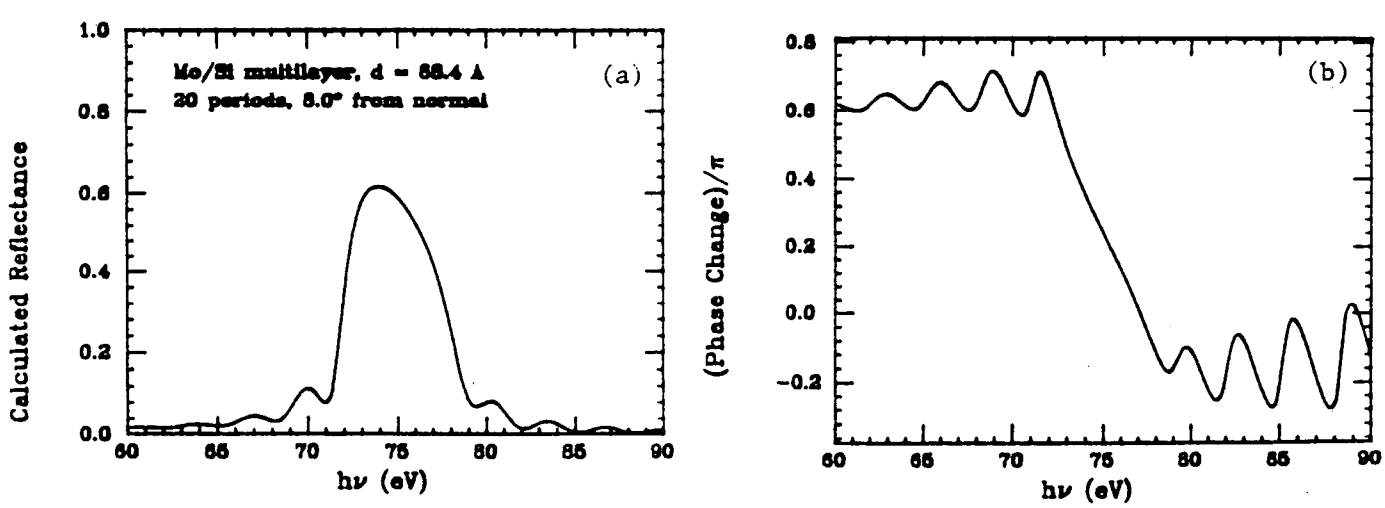

Fig. 2. Calculated reflectance vs. hν for a Mo/Si multilayer having 20 periods each of 88.4 Å at an angle of incidence 8° from normal is in (a). In (b) is the calculated phase change on reflectance.

reflection changes roughly linearly by almost π on going across the multilayer Bragg peak. Thus, the variation in period should be less than roughly the same fraction of the Bragg peak width to satisfy this criterion.

Thus departures in d from the optimal variation across the surface of a single mirror of as much as several percent might be considered acceptable for the multilayer considered here. Considering both mirrors of the SO, the appropriate sum of the departures from optimal period across the two mirrors should be less than this value.

For each of these criteria, the magnitude of acceptable departures from optimal variations in d is set by the bandwidth of the multilayer, which is relatively large for Mo/Si multilayers and $h\nu < 100$ eV. Multilayers having significant near-normal incidence reflectance at higher energies typically have significantly narrower bandwidth and correspondingly tighter tolerances for acceptable variations of multilayer periods across each mirror.

3.2. Assumptions

Several assumptions on which the analysis rests are stated here. We assume that we can deposit a multilayer on a flat substrate with a high degree of uniformity. We also assume that the variation in d for a multilayer deposited onto a curved surface can be separated into variations dependent only on the local height h of the surface and on local angle α that the surface makes with respect to the surface of the sputtering target (see Fig. 3). Further it is assumed that we can measure these dependencies on h and α. These assumptions will be addressed further in the next section. The dependence of the multilayer period on h and α are next assumed to be homogeneous across the surface of each optic, which effectively allows us to assume azimuthally symmetric variations of d about the optic axis of each mirror and hence to consider only the variation radially outward from that axis.

3.3. Sputter deposition system

The obtained variation in multilayer period across a flat or curved surface depends very strongly on the specific multilayer deposition apparatus used. Our magnetron sputtering system has 10 cm diameter, disk shaped sputtering targets facing upwards disposed around a circle with radius 17.8 cm in the baseplate of the vacuum chamber.

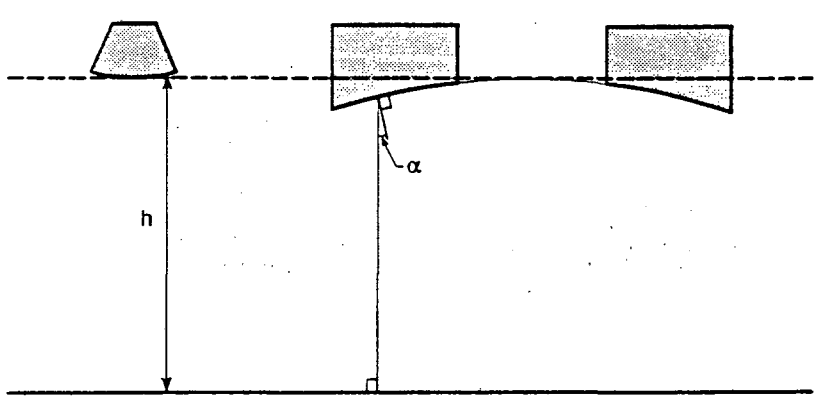

Fig. 3. Primary and secondary Schwarzschild mirrors as oriented in the sputter deposition system. The variation in multilayer period on local angle α and height h can be determined. The apices of the two mirrors are set relative to each other to optimize the overlap of the Bragg peaks of the multilayers on each mirror.

Substrates rotate on a circle whose center is common with that just mentioned, at a distance of 10 cm above the sputtering targets, with one multilayer period deposited in one rotation. To date we have not implemented planetary rotation of the substrates, which can aid in achieving improved uniformity. Rather, for uniformity across a flat substrate we rely on carefully shaped apertures placed immediately below the substrates. These apertures effectively equalize the integrated deposition seen by all points on the passing substrate. Using such apertures we minimize variations in multilayer period to less than ± 1.5% across a 75 mm field orthogonal to the direction of substrate rotation for a flat substrate.

We assume that for a curved substrate, the variation in d is a function of the local height, h, of the surface from the sputtering target plane and of the local angle, α, of the surface from this plane (see Fig. 3). These dependencies are assumed separable, so that $d(\alpha,h) = d_0 \cdot f(\alpha) \cdot g(h)$ where $f(\alpha)$ and $g(h)$ are the individual dependencies and d_0 is the period at some reference point on the curved surface. It is straightforward to measure $g(h)$ and $f(\alpha)$ by determining the variations in period on flat substrates positioned at different values of the dependant variables α and h which span the range of these parameters occupied by the curved surfaces to be coated. These variations were measured by determining d with good precision from measurements of the x-ray (λ=1.54 Å) specular reflectance profile over several orders of multilayer Bragg reflection from multilayers deposited on flat substrates positioned at different h and α values. To a good approximation $g(h)$ varies linearly over the range of h of interest, with a rate of change in d of 0.9% per mm change in h. The functional form of $f(\alpha)$ over the range of α of interest is close to being directly proportional to $\cos(\alpha)$. These measured $f(\alpha)$ and $g(h)$ can then be used to predict the variation of d over the clear apertures of the primary and secondary mirrors of the Schwarzschild objective.

3.4. Application to 20X system

The largest set of Schwarzschild objective mirrors which we have coated to date form a 20X reduction system for the MAXIMUM project. Specific optical design considerations of the Schwarzschild objective and the undulator beamline optics which

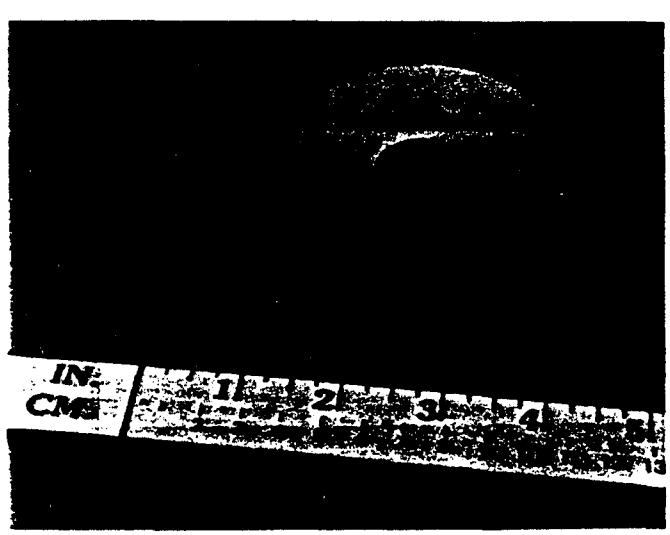

Fig. 4. The coated primary and secondary mirrors of a Schwarzschild objective for the MAXIMUM project at the Synchrotron Radiation Center (University of Wisconsin, Madison).

illuminate it will be presented elsewhere. The 20X demagnification, together with the need for significant working distance between the SO and the sample, resulted in mirrors whose sizes can be roughly gauged in Fig. 4. The analysis outlined above was applied to these optics before they were coated with multilayers to determine if improvements in control of the multilayer period variation were needed.

The analysis combines geometrical ray-tracing through the SO to determine θ values, with the predicted variation of d across the two mirrors to calculate λ by the Bragg equation for all rays at each mirror. From the dispersion in this predicted λ across each mirror we assess issues of multilayer uniformity. The results are summarized in Fig. 5. All plots in Fig. 5 have as abscissa the off-axis angle U of the rays before they reflect from the primary mirror. Rays corresponding to U less than 0.28° are obscured by the primary mirror, leaving an annular clear aperture. Each plot in Fig. 5 has a solid curve corresponding to the primary and a dashed curve corresponding the secondary mirror of the Schwarzschild objective.

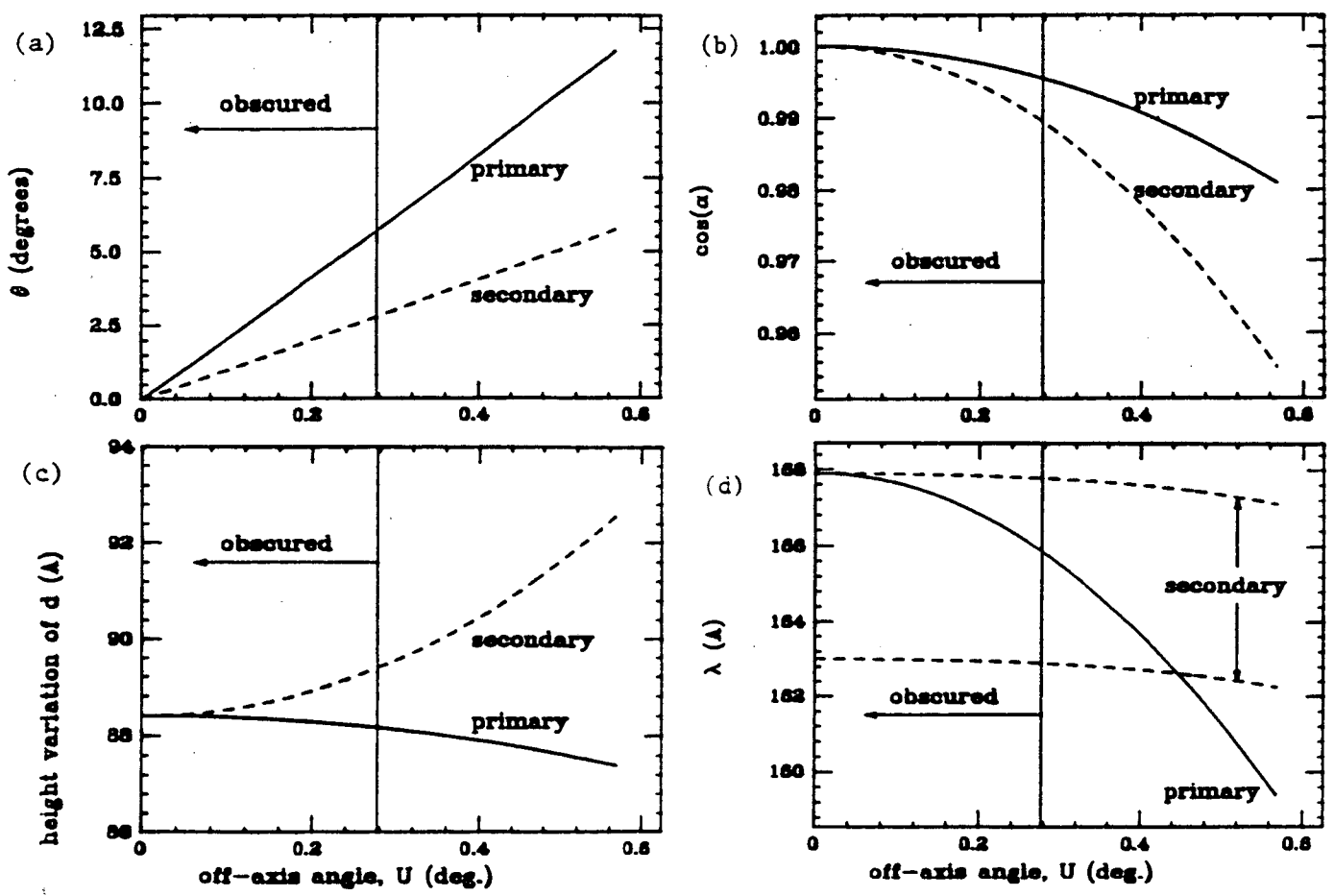

Fig. 5. Results of analysis applied to a 20X Schwarzschild objective. All plots have initial off-axis ray angle U as abscissa, and the solid and dashed curves correspond to the value for that ray at the primary and secondary mirrors, respectively. (a) shows the incident angle at each mirror. (b) and (c) show the predicted deposition angle and height variations, respectively. (d) shows the peak wavelength calculated by Bragg's law using the θ and d dependencies in the previous plots. In (d) there are two curves for the secondary mirror corresponding to two dirrerent heights of that mirror in the sputtering system. The lower curve maximizes the overlap of the primary and secondary curves in the clear aperture.

Figure 5(a) shows the range of incident angles (from the normal) at each mirror made by the various rays. These are the angles θ in the Bragg equation, which yield the ideal variation of d across each mirror as $d = \lambda/2\cos(\theta)$. This equation gives the correct variation of d for the different rays, though refraction effects must be included to obtain the actual d values. θ is always larger for a given ray at the primary than at the secondary mirror. These ranges of θ values yield an ideal variation of period across the primary mirror of almost 2 %, and less for the secondary mirror. The ideal variation in d would have d increasing away from the optic axis for each mirror.

The predicted variation in d across each mirror is obtained from the combined deposition angle and height variations shown in Figs. 5(b) and 5(c) whose measurement was discussed in the previous section. Fig. 5(b) shows the predicted variation $f(\alpha)$ resulting from the changing angle α at each point on each mirror. The results assume that each mirror is oriented with its optical axis normal to the plane of the sputtering targets. The deposition angle dependence for d is in the same direction for both mirrors and is strongest for the secondary, changing by several percent over the clear aperture of this mirror. Fig. 5(c) shows the deposition height variation $d_0 \cdot g(h)$ assuming that the apex of each mirror is at the same height in the sputtering system (to give d = 88.4 Å at each apex). The variation in g(h) goes in different directions for the two mirrors. For the primary mirror the height variation adds to the angle variation to produce a larger overall variation, while for the secondary mirror the two variations partially cancel.

One representation of the results of the analysis for this Schwarzschild system are in Fig. 5(d), which shows the predicted peak wavelength calculated from the Bragg equation as obtained using the incidence angles θ from ray-tracing and the predicted variation in d shown in Figs. 5(b) and 5(c). Two dashed curves for the secondary represent predicted variations in d obtained from positioning the secondary mirror at two different heights in the deposition system. The lower dashed curve has the height of the secondary mirror selected to maximize the overlap of λ in the clear aperture in this plot radially outward from the optic axis of the system.

4. Discussion

The results presented in Fig. 5(d) allow us to gauge the effects of the predicted variation in multilayer period on the performance of this 20X Schwarzschild objective. The predicted dispersion for λ of the secondary mirror across the clear aperture is much less than 1%, while for the primary it is about 4%. By arranging for the peak λ for the two mirrors to intersect in the middle of the clear aperture, i.e., using the lower of the two dashed curves in Fig. 5(d), we reduce the difference in Bragg peak wavelength to roughly 2% across the clear aperture. This is just within the acceptable limits of multilayer period variation set by the first criterion in section 3.1. From this analysis we concluded that no significant modification of our multilayer deposition system was required to obtain an acceptable variation in multilayer period for this SO system.

The same conclusion would not necessarily be reached for other Schwarzschild objectives, however, for at least several reasons. First, the dispersion in λ predicted by this analysis depends on the optical design of the SO. This analysis applied to a 100X demagnification design[7] predicts a dispersion in λ of roughly 9% across the clear aperture, which is larger than what would be considered acceptable by the criteria mentioned above, assuming the same multilayer bandpass. Thus assuming SO illumination with x-rays having a narrow bandwidth, only an annular

region within the clear aperture would reflect with high efficiency for this design. Second, multilayers having bandpass significantly smaller than that of Mo/Si for hν < 100 eV considered here would not meet the uniformity criterion for the 20X system discussed here. As hν increases above 100 eV absorption lengths generally increase, and multilayers having significant near-normal incidence reflectance have much smaller Bragg peak bandwidth. Thus, while variation in multilayer period for the case considered here does not appear to pose real problems, Schwarzschild objectives having different magnifications and/or coated with narrower bandpass multilayers will require more attention to control of the variation of multilayer period.

Initial results using the multilayer coated SO described in this paper have recently been obtained, and will be reported elsewhere. The goal of this project is to demagnify an illuminated pinhole to form an intense sub-micron spot, and one result of initial experiments is relevant to this discussion. The size of the focal spot appears to be determined by vibrations in the optical system, rather than by other factors such as figure error or unacceptably large variations in multilayer period across the optics. The same conclusion was reached in a laboratory SO system by Trail.[6,7] Thus the contribution of variations in multilayer period to blurring of the focal spot are not actually known at this time, though this contribution is expected to be small.

Finally we recall that many assumptions were made in the analysis regarding specific aspects of multilayer deposition in our sputtering system. Those assumptions which lead us to treat the deposition as azimuthally symmetric with respect to the optic axis allowed significant simplification of the analysis. These and other assumptions are being checked by more detailed characterization of deposition in our sputtering system. Also, spatially-resolved near-normal incidence reflectance measurements from the multilayer coated optics described here are being made at the SURF facility at the National Institute for Standards and Technology. Early results of these characterizations suggests that departures from these assumptions are within the acceptable limits discussed above.

SUMMARY

A method for analyzing the effect of a d-spacing variation on the performance of multilayer coated Schwarzschild objectives has been presented. The analysis combines geometrical ray-tracing to obtain the incident angles on each mirror for the different rays, with the predicted variations of multilayer periods across each mirror, and uses multilayer interference theory to provide criteria for acceptable variations from ideal behavior. For Mo/Si multilayers at photon energies below 100 eV their bandpass (7-8%) is large enough so that predicted variations in multilayer period in our sputtering system do not appear to present a problem. For systems using multilayers with narrower bandpasses or having larger dispersions across the clear aperture, active control of multilayer period across the mirrors will be required to achieve optimal imaging performance over large clear apertures.

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