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Fabrication, alignment and test of an all-reflective, soft x-ray microlithography objective

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ABSTRACT

A 20 power (20X) all-reflective microlithography objective has been fabricated for use in the soft x-ray region at a wavelength of 13 nm. The design uses the Schwarzschild configuration where two spherical mirrors form a point image from a point object. The centers of curvature of the two mirrors in such a system are coincident. However, to increase field of view, fifth-order spherical must be balanced by third-order spherical. This is accomplished by separating the two curvature centers longitudinally. Lateral separations quickly introduce coma into the wavefront. Holding the curvature center positions rigidly in place relative to the object and image positions is required for maintaining the wavefront quality. Suitable x-ray sources are not common; therefore, the rigidity must also be viewed as a level of ruggedness suitable for transportation from the assembly facility to the test facility.

In this paper we will share the techniques that we have used to satisfy the requirements of MTF, wavefront quality, ease of alignment, and ruggedness. The MTF goal was 50 percent modulation at 10 lp/µm. The P-V wavefront quality goal was $\lambda/2$ at the 13 nm wavelength, corresponding to having a wavefront of $\lambda/100$ at the more familiar 632.8 nm wavelength. Obviously, the two mirrors must have excellent surface quality characteristics to start with, and they must be held in such a way as to not change their shape and yet allow for positioning freedom to accomplish the alignment. The wavefront quality requirement results in lateral positioning tolerances at the micron level. Once the alignment has been achieved, the mirror positions must be fixed to this same level of accuracy. To preserve the alignment, the mirror positions must be held in a manner which does not impart strain into the mirrors or housing. For example, we must avoid a situation where tightening a screw down to hold a part in place compresses the part (changing its shape) and twists the part (introducing strain). Meeting the ruggedness requirement ensures that the objective will not require realignment every time it is moved to a new facility.

A second objective has already been designed and is being fabricated. It is larger in size, and provides 10X magnification while maintaining the base Schwarzschild design. Changes in the performance requirements have caused some mechanical redesign, but the overall alignment philosophy has been retained. We conclude by giving examples of the performance achieved for both the 20X and 10X configurations.

1. INTRODUCTION

Soft x-ray projection microlithography is a newly developing field which challenges numerous optical engineering disciplines. These optical systems operate at a wavelength of 13 nanometers, a value nearly fifty times less than the visible region where most optical engineering experience prevails. The major consequence of this wavelength scaling is that all optical and mechanical tolerances must scale proportionally in order to achieve diffraction-limited quality. Prototype projection lens objectives with magnifications of 20X and 10X have been designed and fabricated to provide proof-of-concept information on system performance, coatings, optical surface quality, and alignment tolerances. In the following sections we will detail the methods we have used to successfully construct a 20X objective, and present the results of the 20X and an improved 10X objectives. This paper will concentrate solely on the alignment issues associated with this research program.

2. OPTICAL DESIGN

The Schwarzschild microscope objective is the design form of choice for this program. Figures 1a and 1b present two schematic views of the Schwarzschild objective consisting of a small convex primary mirror and a large concave secondary mirror. The two optical surfaces are nearly concentric, as indicated by the fact that the centers of curvature of the two surfaces are nearly coincident with each other. The third order spherical aberration in the Schwarzschild instrument is nominally zero, but the departure from concentricity allows higher orders of spherical aberration to be balanced against third order. The system is used in an off-axis configuration so there is no obscuration present. The system provides a field of view large enough for the proof of concept demonstration, and since the surfaces are spherical they are relatively easy to fabricate. Also, because only sections of the spherical surfaces are used, it is possible to pick and choose the "sweet spots" of both mirrors in order to ensure highest quality wavefront performance.

The optical axis between any two spherical surfaces is defined as the line passing through the centers of curvature of each surface. By extending this line to where it intersects the image and object planes we have defined the center of these planes, as well. Since the centers of curvature of these two surfaces are so close to each other (90 microns), any tilt or decenter of one surface with respect to the other will have a major impact in the angular displacement of the centerline between these points. This can cause a large motion of the optical axis. Therefore, as one will see, one of the main alignment objectives which must be met is the maintenance of the relative positions of these points to a high tolerance.

3. PERFORMANCE AND ENGINEERING GOALS

The major performance goal of the research effort was to produce an optical system yielding an MTF of 50 percent at a spatial frequency of ten line pairs per micron. The major engineering goal was to design and build a system which provided for smooth and accurate adjustments, that could be locked in place without disturbance during the locking process, and could be ruggedized to meet transportability and handling requirements. Finally, the correct mechanical interfaces had to be developed to mate with the x-ray beam sources.

Theoretically, a Schwarzschild system is relatively easy to align. However, in practice the major challenge faced in this optical system was the tight tolerance requirements associated with these relatively simple adjustments. These adjustments included:

1. Control of the spacing between the primary and secondary mirror in order to balance third and fifth order spherical aberration over the diameter of the off-axis aperture depicted in Figure 1a. Tolerance analyses indicated that in order to meet the RMS wavefront and MTF requirements, the spacing should be controlled to better than ± 10 microns.

2. As previously mentioned, small decentration of one of the two centers of curvature with respect to the other tilts the optical axis by a large amount - 1.5 microns of displacement tilts the optical axis by one degree. This, in turn, has the effect of moving the already small image at the image plane by amounts which are large enough to affect image quality. Consequently, in order to meet MTF and wavefront requirements, decenter had to be adjusted, set, and maintained to the one micron level.

3. An accurate, reliable, stable, and simple method of focussing the image plane.

An alignment philosophy was devised which, if successfully implemented, should meet the above mentioned performance and engineering goals. We now discuss some of the more important points in the alignment philosophy.

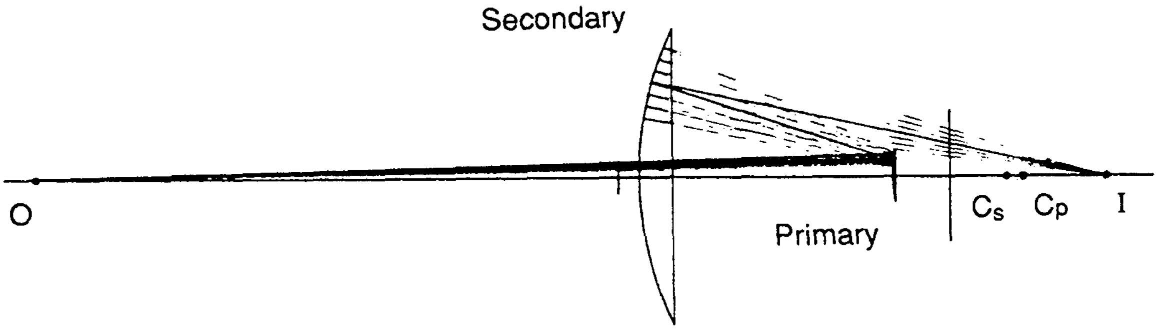

Figure 1a. Side view of the Schwarzschild objective.

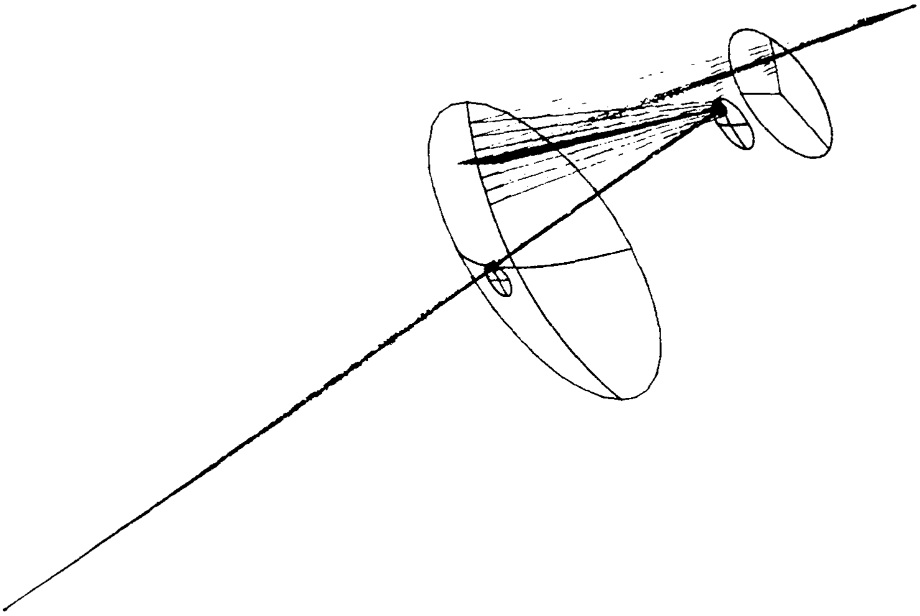

Figure 1b. Isometric view of the Schwarzschild objective.

4. ALIGNMENT PHILOSOPHY

Several design choices had to be made, but specific alignment considerations controlled the design direction. The special considerations outlined below help to form the basis of our overall alignment philosophy.

Massive microscope objective body: Since weight is not a particularly driving issue in this program, it was decided that the main structure holding the optical components and their adjustments would be relatively massive. Figure 2 shows the basic mount. A massive structure is also more thermally stable and less likely to go out of alignment during small temperature excursions.

Kinematically mount secondary mirror: The larger of the two mirrors in this microscope objective is the concave secondary mirror. It is quite massive to prevent surface distortions due to mechanical deflections. It was mounted as shown, using its optical surface as the mounting interface. Using this method, alignment or centering of the secondary mirror's center of curvature to the mechanical axis to a high level of accuracy was all but assured. As long as the mirror remains in contact with the three points, any slight slippage of the mirror in the mount would not move the center of curvature point, and thus would not affect alignment. Note the use of opposing force points which minimize deformations to the mirror surface.

Use shims for adjustment of primary to secondary mirror spacing: Shims are used to adjust the spacing between the primary and secondary mirror, allowing for the correct balance of third and fifth order spherical aberration in order to minimize zonal spherical across the off-axis aperture used in the system.

Tilt the primary mirror in order to create a decenter at the center of curvature: This is used to minimize coma. Provision for smooth, continuous motion allows the coma to be "dialed out", i.e. removed, while observing the wavefront with an interferometer. Figure 3 depicts the gimbal ring concept which supports the primary mirror. The outer ring holds the mirror and rotates about a single axis relative to the middle ring. Flex pivots are used to form the rotation axes and provide smooth motion with no stiction or backlash. The middle ring rotates, relative to the inner ring, about a second axis that is orthogonal to the first rotation axis. Both rotation axes lies in a plane perpendicular to the opto-mechanical axis of the housing. The inner ring attaches to the housing and sits on the shims which control the inter-mirror spacing. Figure 4 depicts the lever arm assembly which provides a 10:1 motion reduction. The screw at one end adjusts the lever position. Its motion is minimized 10 times to the ball which sits near the pivot point. The ball pushes against the gimbal ring and a spring provides the restoring force. The screw provides a limited motion adjustment range. Different size balls are furnished to provide the coarse adjustment position.

No exposed adhesives: Adhesives could not be used in the mounting of components because exposure to the x-ray environment causes carbonization which damages the optical coatings.

Use shims for precise focus control: A coarse shim is used to achieve the approximate focus position. The fine shimming action is performed using three precision steel balls of identical diameter. The three balls provide the three-point surface of support used by the silicon wafer. Additionally, the three balls are part of a set graduated by diameter steps of 5 millionths of an inch. Final focus is determined by changing the three ball sets until the best imagery is found.

Logical and concise alignment plan: The four points of interest along the optical axis are the centers of the object and image planes, and two centers of curvature points. The initial alignment process makes use of the object, image, and secondary mirror center of curvature. The alignment fixture is configured to hold the optical axis vertical with the object plane at the bottom. This layout eliminates gravity induced misalignments. It is also the configuration of actual use. The longitudinal position of the secondary mirror within the housing is fixed -- the optical surface butts up against three hard mounting points. Its center of curvature is then also fixed in place. Its center of curvature position is found using a beamsplitting microscope. The nominal optical prescription provides the expected image-to-secondary mirror center of curvature distance which can be set and verified using the beamsplitting microscope and a plate which sits on the three focus balls.

The expected object-to-image distance is also provided by the optical prescription. It is set using a calibration rod which is rounded on one end, squared off on the other, and set to the object/image distance minus a tooling ball radius. This tooling ball will be located at the object position and allows the interferometer to be properly oriented with the housing. The rod is lowered down through the housing until the flat end rests on the tooling ball. When the tooling ball height is properly set, a flat plate on the three focus balls will barely touch the rounded end of the calibration rod. The lateral

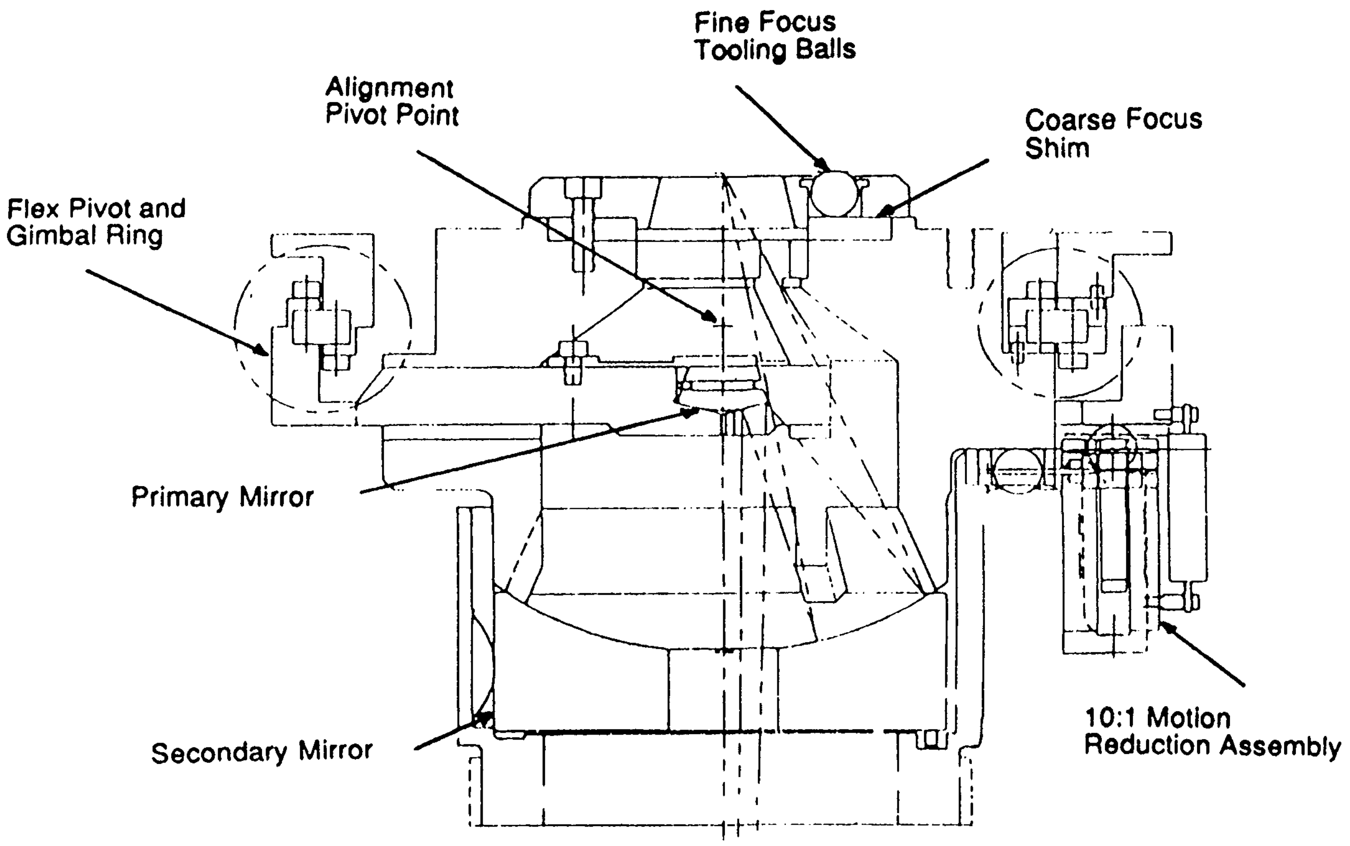

Figure 2. 20X projection assembly housing cross-section

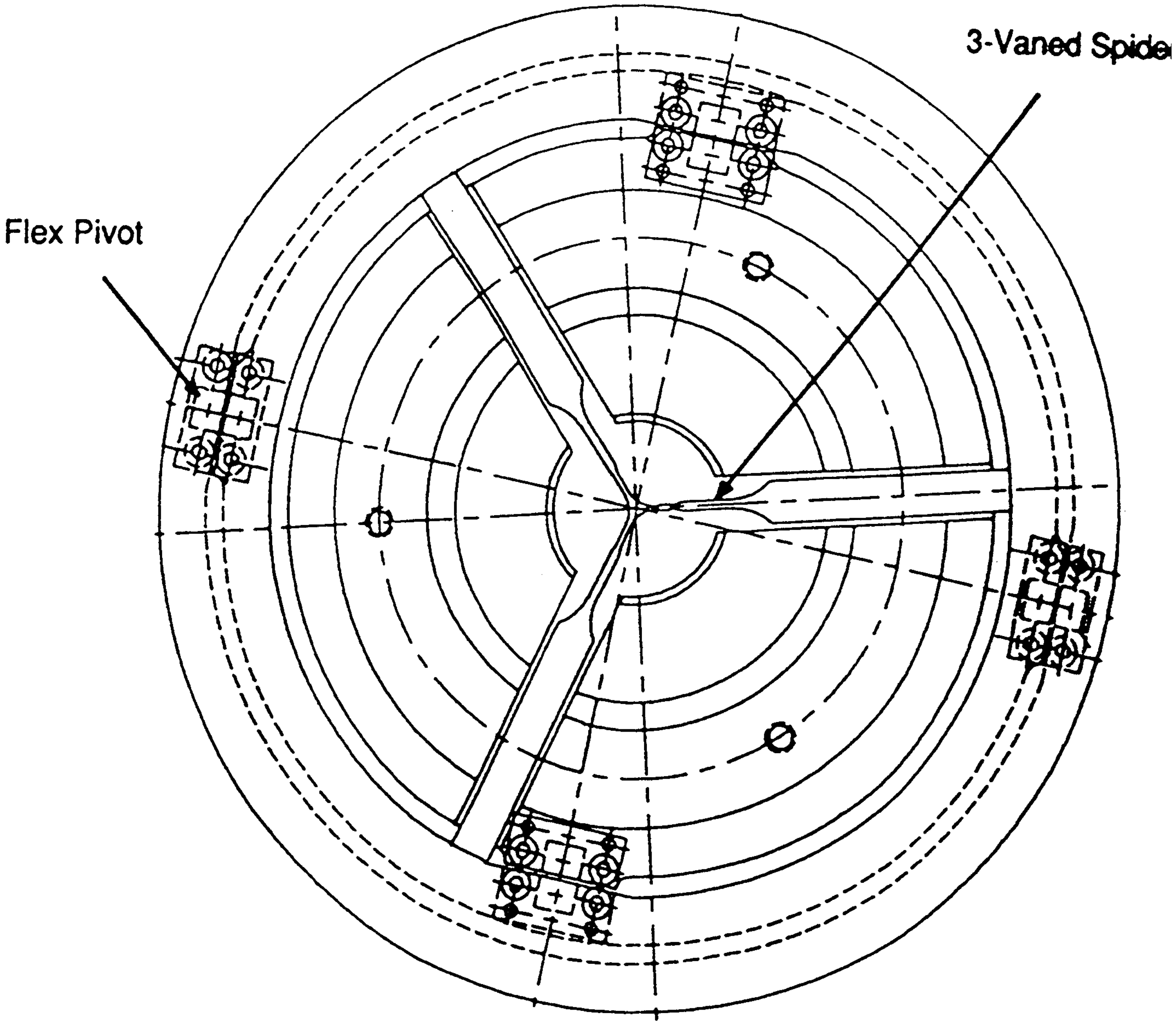

Figure 3. Gimballed primary mirror mount

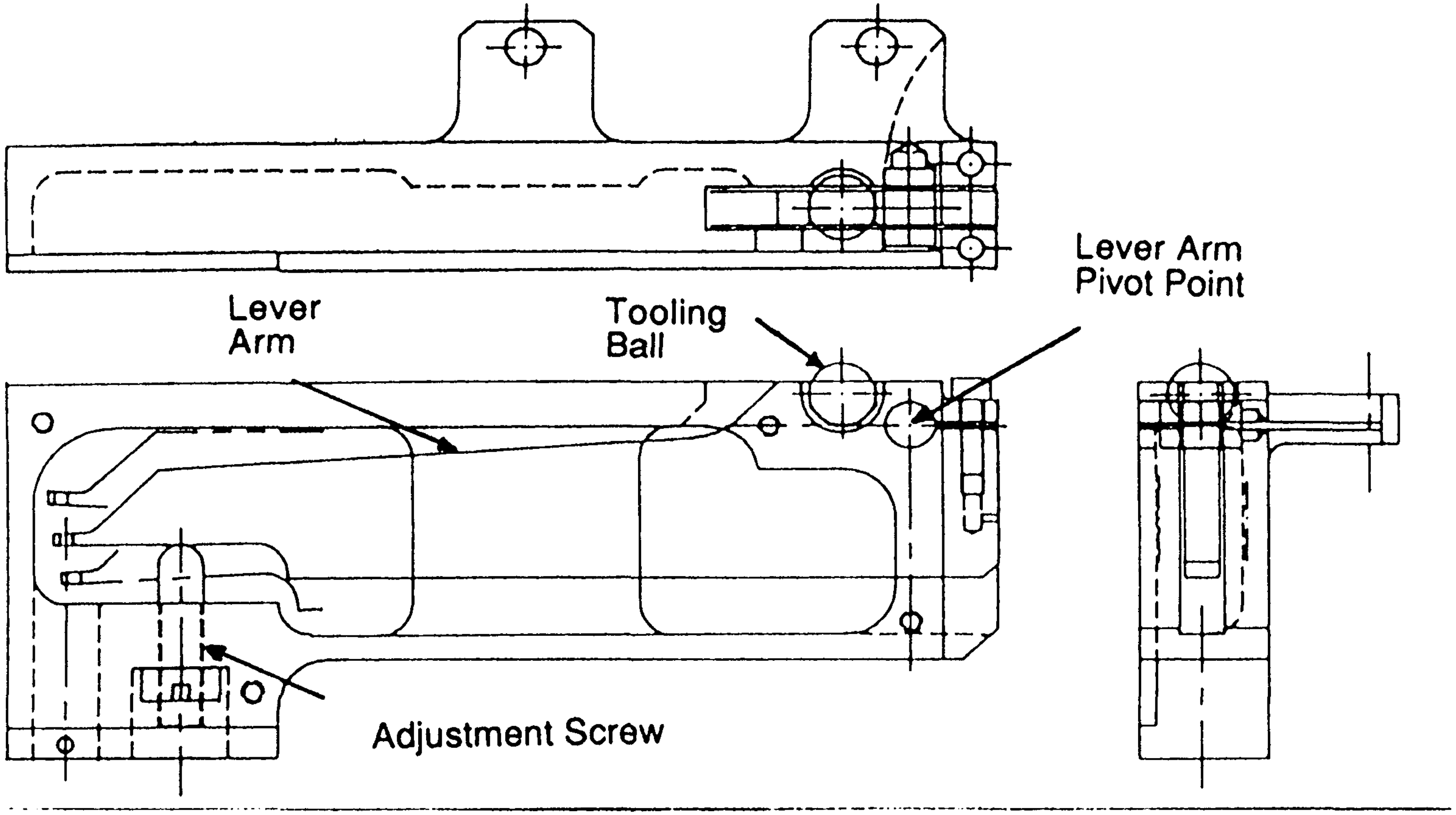

Figure 4. 10:1 Motion reduction assembly

positioning tolerances on the tooling ball are loose enough that its position is checked by simply illuminating it with a collimated beam (previously made perpendicular to the image plane using a flat mirror as the reference) and centering the shadow within the aperture. Clearly, the ball should be small enough so that its shadow is smaller than the smallest aperture.

This alignment plan provides for the logical process by which the opto-mechanical axis is defined, and the object, image, and secondary mirror are correctly positioned relative to each other. The remaining alignment task involves alignment of the primary mirror to the secondary mirror while maintaining this opto-mechanical configuration. These adjustments use the spacing shims under the gimbal assembly to vary the intermirror spacing. The gimbal allows the primary center of curvature to be positioned smoothly in the lateral direction, and the coarse focus shim and/or focus balls can be changed, if needed, in order to accommodate small deviations in the values of radius for the two mirrors.

Note that this alignment uses the full objective aperture. Only after the mechanical positioning is achieved would the subaperture be inserted at the position of the least apparent wavefront error. If necessary, the two mirrors could be "clocked" , i.e. azimuthally rotated, with respect to each other to better balance local mirror surface errors and achieve the best subaperture wavefront. Figures 5 and 6 provide additional explanation and an example of the technique.

5. SYSTEM PERFORMANCE

In order to confirm that the alignment was complete, the 20X objective was transported to the x-ray source location and tested. After adjusting for the final focus, it was found that the 20X system was able to achieve a resolution of better than 10 lines per micron (modulation approximately 50%) in the tangential direction, but had significantly poorer resolution in the radial direction. These results were to be expected.

Imagine a grid of points across an optical surface. At each point we produce a vector equal to the direction and magnitude of the surface slope error at that point. These vectors will have both a radial and tangential component to the slope. The dominance of a radial slope component over the tangential slope component (or vice-versa) will affect image quality in these two orthogonal directions. If the dominant component is radial, then it is unlikely that optical system performance can be improved through a rotational clocking of one optical component with respect to the other. However, if the tangential slope error is the dominant form across the surface of the mirror, it is possible that correct clocking of the surfaces can improve image quality. In the case of the 20X system, we noted from the wavefront contour plots that the surface slope errors were primarily radial in nature. Interferometric analysis of the 20X concave secondary revealed that two high zones occur in the annulus region separated by a low zone. As the subaperture contains at least one high and one low region, it was impossible to clock the mirrors to locate a "sweet spot". No position would give significantly better performance.

Knowledge of this problem was used advantageously in the fabrication portion of the 10X development, and no zonal areas are apparent in any 10X mirrors. These mirrors do suffer from residual amounts of astigmatism which, having widely separated high and low regions, can be successfully removed by the clocking operation. The interferometric analysis of the 10X system predicts an RMS subaperture wavefront of 0.065 to 0.090 waves for the 13 nm wavelength (see Figure 6). The large range is due to using the normal interferometric line of 632.8 nm for test and alignment, giving RMS values of 0.001 and 0.002. Actual x-ray testing of the 10X objective will occur upon completion of the mirror coating process.

6. CONCLUSIONS AND FUTURE CHALLENGES

Soft x-ray projection microlithography has been validated through the successful development of the 20X Schwarzschild microscope. This proof-of-concept instrument has shown to be capable of resolving ten line pairs per micron with a modulation of fifty percent. The alignment challenges of developing a system that is rugged yet easily adjustable were also achieved. It should be noted that this success was based not on pushing the state of the art, but rather making best use of the currently available technology. From the test results discussed in this paper, it appears that optical fabrication and testing techniques pose the greatest barriers to further increasing the state of the art of this technology.

The future challenges will be concentrated on developing technologies that will allow for a wider field of view. The goal is to develop fields of view that will permit exposures of 25 mm diameter wafers. More complex optical configurations will be required in order to do this, possibly introducing aspheric optical surfaces as required to both widen the field of view and minimize the number of reflecting surfaces in the system. As aspheric surfaces have well defined optical axes, the alignment challenges will also increase in these future systems.

Reducing Effect of Fabrication Errors by Clocking

- Fabricate multiple copies of the elements (10 primaries, 8 secondaries).
- Measure figure error using PMI.
- Match elements and numerically clock to minimize wave front error in the x-ray subaperture.
- Apply multilayer coatings on selected elements.
- Remeasure and reclock coated elements.
- Align objective using the indicated clock angles.

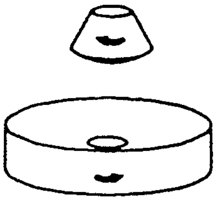

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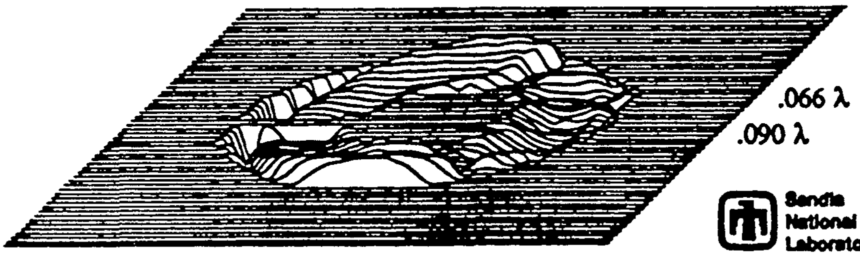
Figure 5. Description of "clocking" technique for optical wavefront improvement.

Clocking Optical Elements Achieves Design Wave Front Error (.066 λ rms at 13 nm)

Predicted Objective WFE



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Measured Objective WFE

Figure 6. Example of predicted and measured subaperture wavefront errors for the 10X objective.