Proc. of SPIE Vol. 0483, Optical Alignment II, ed. M.C. Ruda (Jan 1984) Copyright SPIE

Alignment of Precision Lens Elements

Robert E. Hopkins, Kenneth F. Walsh

Optizon Corporation, Rochester, New York 14623

Abstract

A major limitation on the performance of lenses is the accuracy with which the elements can be centered. Most methods for alignment of lens elements require rotation of the elements in a precision bearing. Small lenses are difficult to manipulate with precision while mounted in a rotating bearing. A method is described which does not need rotation to center the elements. The advantages and requirements of such systems are analyzed.

Introduction

Some of the modern lenses used for photolithography and laser applications require diffraction limited performance for reasonably wide fields of view. A diffraction limited lens is essentially an interferometer and its construction has to be undertaken with interferometric precision. The optical surfaces have to be made as spheres to within 1/10 wavelength, thickness and centering tolerances sometimes have to be held to within a few micrometers.

Some remarkable results can be achieved in image performance of lenses if one is willing to use critical air spaces as illustrated in the lens shown in Figure 1. This lens is a micro-objective (3.6mm EFL and NA = 0.66). The lens is designed to form an on-axis image which is corrected to 1/8 wave. The alignment method to be discussed in this paper concentrates on placing the center of curvature of each surface directly on a single optical axis. The micro-objective was toleranced by decentering each surface (one at a time) by a given amount. The decenters introduce coma. Table 1 lists the tolerance on the individual surfaces based on accepting no more OPD than 1/8 wave. These displacements suggest severe mechanical problems in mounting the lenses, and rule out dependence on edge centering.

Surface #	Δd (micrometers)	Δd (Inches)
2	200.	0.008
3	1.6	0.000063
4	2.2	0.00008
5	2.5	0.00008
6	200.	0.008
7	2	0.00008
8	3	0.00012
9	2	0.00008

Table 1. Displacement tolerances for decenter (Δd) of the surfaces shown in Figure 1.

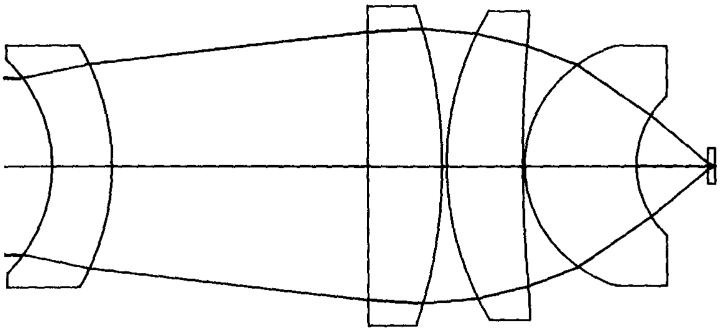

Figure 1. A diffraction limited micro-objective EFL=3.6mm, NA=0.66

Most optical shops will avoid the use of such surfaces because of the difficulty in mounting the lenses centered and properly spaced. Some modern requirements for lenses make this option worth the development of techniques in lens mounting and testing. This paper will discuss methods that can be made to achieve high accuracy in centering. When matched with modern interferometric testing of individual surfaces, it should be feasible to manufacture new lenses with outstanding performance.

Standard Methods for Mounting Lenses

The standard method for mounting lenses is to edge the lenses and use the barrel to align them on a single optical axis. This method is adequate for most lenses manufactured in large quantities. The elements are usually edged on self centering machines. The next level of precision requires lenses that are optically centered, and the mounting clearances between the edges of the lens and the lens barrel are tighter. As one tries to increase the precision in the centering, several difficulties are encountered.

Edging a glass lens to a precise diameter while centered is not a task well suited to the optical shop. It is difficult to hold the lens on a chuck and to have the equipment to check that both surfaces run true with respect to the edge being ground. The optical shop is a hostile environment for the optical and electronic tools required to make measurements with micrometer accuracy.

As long as the lens is to be centered by its edge, the clearance between the edge and the barrel must be small. This introduces problems in inserting the lenses into the cells and may introduce strain if there are temperature changes. The barrel may have several internal diameters which have to be turned on exactly the same axis.

The spacers between the lenses must contact the lenses at the correct diameter or the spacing will be incorrect. The spacers may warp after removal from the lathe. The spacer may have feathered edges which can be dented. Almost every cut made on a spacer has to be precise in order to assure precision spacing and centering in the barrel.

Some manufacturers mount precision lenses in separate lens cells in which the lens is held with cement, a precision retaining ring or by burnishing a ring of metal onto the lens. Usually the lens edge is not used to center the lens in the cell. The lens is centered in the cell on a mounting ring. It is then moved about until the top surface runs true. This is checked in much the same way as one checks the centering of the lens when it is being optically centered on a centering machine. After the lens is mounted, the cell can be inserted in the barrel with very little clearance. This method can be made to provide excellent lenses but great care has to be taken in making all the cells. There are several precision cuts that have to be made on every cell. Usually rough cuts are made and then the part is removed from the lathe and the cell heat treated to relieve strain. The part must then be repositioned in the lathe and the finishing cuts made fine enough so that no further warpage takes place.

Cell Mounting

The method to be described for mounting lenses is cell mounting. There are several conditions believed necessary for precision lens assembly. The edging of the lens in the optical shop should have moderate centering tolerances. Most optical shops should be able to meet the centering requirements. The final alignment of the lenses will not be dependent on the edge of the lens. No precision bevel on the lenses should be required. The lenses should be aligned in the cells so that the lens optical axis is perpendicular to a horizontal reference surface. The lens alignment should be achieved without the need for a rotating bearing. The lens cells should require a minimum number of precision cuts.

Figure 2 is a schematic of a centered lens, positioned in a cell, prior to mounting in the barrel. The primary precision requirement for this cell is that the top and bottom surfaces designated as AB and CD be as flat and parallel as possible. In production it would be desirable to have several of these cells ground together using the type of finishing techniques used by optical shops for making optical flats.

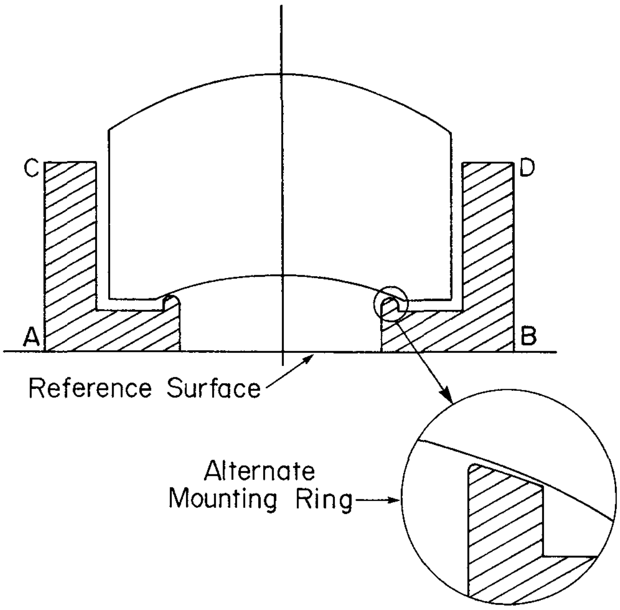

Figure 2. A perfectly centered lens mounted in a cell.

The only other precision requirement for the cell is that the surface mounting ring should be circular and the plane of the ring should be parallel to AB and CD. The mounting ring should have a spherical cut (Figure 2). The glass surface should contact the ring in a ring line contact. If the spherical surface is not used, the contacting points should be made with as obtuse an angle as possible. This refinement is needed to avoid any feathered edge of contact which my result in the lens not seating solidly. In principle it is not necessary have the mounting ring exactly parallel to the surface AB, nor is it necessary to center the mounting ring in the cell. Standard quality machining should suffice for the positioning of the mounting ring. The priorities for precision are, in order of importance: exact parallelism of the surfaces AB and CD; smooth flat surfaces for AB and CD surfaces; consistancy in thickness of the cell for all duplicates of the cell; and the intended mounting ring should be a circle in one plane.

The Interferometer for Aligning the Lenses in Cells

The interferometer proposed for aligning the lenses in their cells is illustrated in a schematic drawing Fig. 3. A typical Twyman-Green interferometer is shown mounted on a precision vertical slide. The interferometer uses a HeNe laser as a source. The instrument is provided with a crosshair at the focal plane of an eyepiece, but is designed so that the eyepiece and crosshair are removeable to allow the observer to view the interference fringes from the viewing lens focal point. The preliminary alignments can be made using the crosshair and eye piece and the final alignment can be made by fluffing out the interference fringes. The interferometer is mounted rigidly to the vertical slide.

Well corrected focusing lenses may then be mounted in the lens port. Once the lens is in place it will form a point image. As the interferometer is moved along the slide, this point focus traces out the reference axis for the lens alignment. It must move along a line perpendicular to the reference surface. This alignment cannot be checked by simply checking that collimated light from the interferometer is perpendicular to the reference surface. One can see that if the slide axis is tilted with respect to the instrument axis, the line traced by the focal spot will be tilted also.

The collimated light from the lens will then be focused at a point which will move on a line perpendicular to the reference surface when the interferometer is moved along the vertical slide. The line of movement of this image point then establishes a reference axis which is used to align each lens in a cell and to align the lens stack. When the lens is mounted in the interferometer there are several reflections which will return and confuse the alignment so it is advisable to use a half wave plate below the lens and polarizers in the interferometer to block these reflections, but allow reflections from the lens being centered to pass thru.

The interferometer must of course be constructed to be rigid. It should be designed to reduce as much as possible the cantilever appearance shown in the schematic diagram. The slide should surround the interferometer. A horizontal slide might be feasible but it is a great advantage to have the horizontal reference surface.

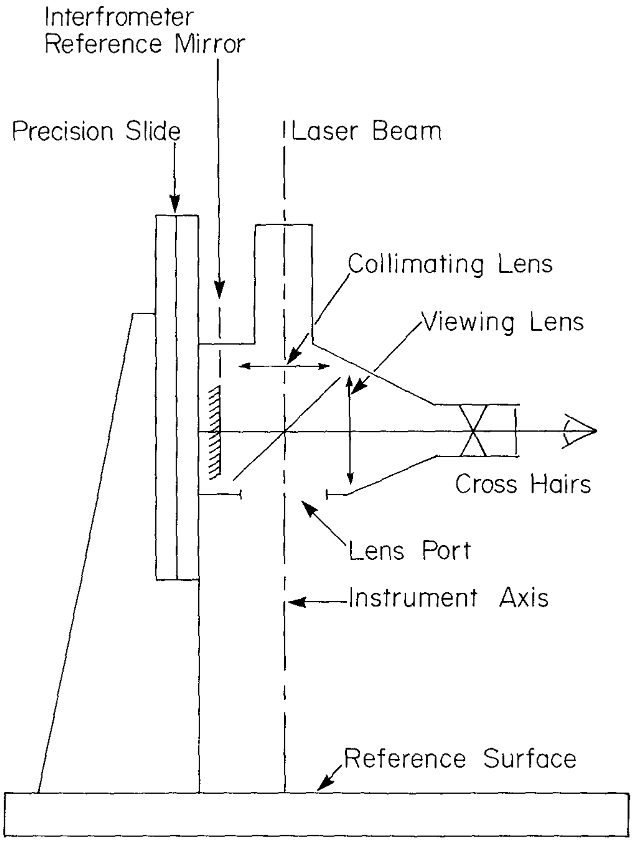

Figure 3.
A vertical interferometer for lens in cell and barrel alignment

The Procedure for Aligning a Lens in its Cell

Figure 4. shows a lens placed upon a lens cell. Its optical axis is not perpendicular to the reference surface. Yaeli[1] has described a method for designating the optical axis of a refracting lens. The following description follows his procedure. The reference optical axis is reflected off the first surface of the lens as reflection S1. The reflection from the bottom surface is reflected as S2. Both of these beams are reflected to the same side of the reference beam. This is true for a negative lens as well. Figure 5 shows a lens placed on the cell with its optical axis parallel to the reference axis but it is not coincident with it. In this case the two reflections S1 and S2 are reflected on opposite sides of the reference optical axis. In this case the lens cell and lens need merely be translated until the two beams come together and then the reflected images will return along the reference optical axis.

The alignment procedure consists of iterating the following two steps:

1. Rock the lens on the lens cell until the two reflected images are evenly spread on the two sides of the reference optical axis as seen in the crosshair.
2. Translate the lens and cell until the two reflected images come together.

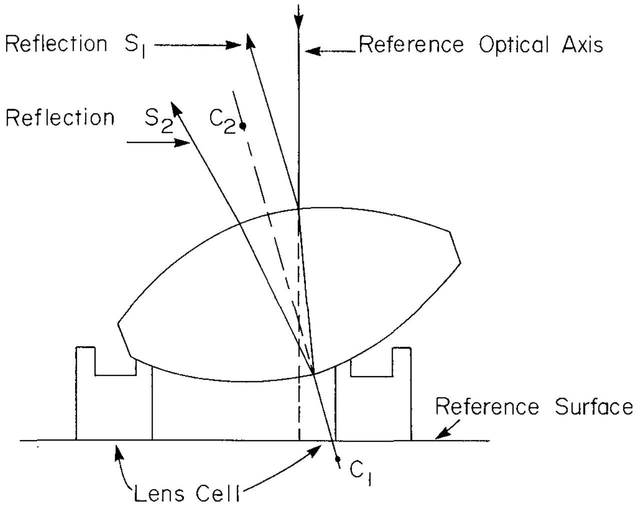

Figure 4.
A lens improperly centered, its optical axis is not perpendicular to the reference surface.

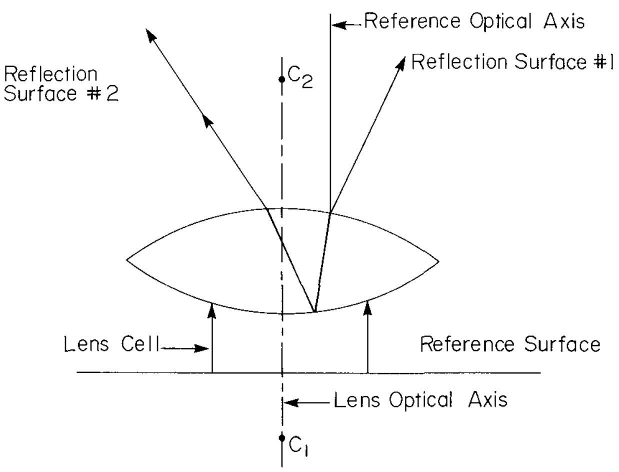

Figure 5.
A centered lens, its optical axis is perpendicular to the reference surface.

This sounds good, but there is a catch. Since a focusing lens is inserted in the interferometer we do not have a single ray as depicted in the drawings. Instead there is a converging beam. This means that the reflected beams will not return to a single point until the focusing lens focal point is imaged at the center of curvature of the lens being aligned. If the focusing lens is focused some place mid-way between the centers of curvatures then both return beams will be out of focus blobs at the crosshairs in the eyepiece. This means that the centering is only as good as one's ability to superimpose two blobs. However the two reflected beams will be coherent, so they will cause circular interference fringes. Since the interferometer has a reference mirror, two sets of circular finges are formed and when the alignment is perfect these two sets are concentric. If the fringes are too fine to see, the alignment has to be done as well as possible with the two blobs. When aligned as well as possible the interferometer should be focused on one of the centers of curvature. Then the return beams will appear as a point and a blob. The alignment steps are repeated until the point appears in the center of the blob. The interferometer should then be reset using the vertical slide to focus on the other center of curvature. If the point image is not on the crosshair, the alignment steps have to be repeated. If the slide moves the focus of the focusing lens on a straight line which is perpendicular to the base reference surface, it should be possible to focus from one center of curvature to the other and have the reflected images stay centered on the crosshairs.

The focusing lens in the interferometer should have as large a numerical aperture as possible to cover a large portion of the surfaces of the lens to be centered. However the centers of curvature of the lens being centered may not be accesible without a long back focus on the focusing lens. This will lead to a large lens. If the centers of curvatures are widely separated it may not be possible to reach both of them within the vertical slide range. It is clear that the interferometer cannot meet the best of conditions for lenses of all sizes. It lends itself best to small lenses. However there are many options for achieving good centering. One can use several different focusing lenses and even a series of reference mirrors in the interferometer. Also, it is not necessary to get to the center of curvature of long radii which cannot be reached with the vertical slide. The surface can be centered with reasonably good sensitivity by focusing near the surface itself. If the beam is focused exactly on the surface the return is a small image but there is no sensitivity. As it is focused above or below the surface the sensitivity increases as the distance increases.[2]

An alternate option is to mount the long radius on the cell mounting ring. If this is done however, the cell mounting ring must be in a plane parallel to the reference surface. (If it is possible to reach both of the centers of curvature it should be noted that the mounting ring does not have to be parallel to the reference surface.)

This method sounds like a fairly involved alignment procedure, but with use lenses can be centered in the mounts easily. A significant advantage can be realized by having a system which does not depend on rotation of a bearing. Tooling can be provided to move the lenses around on the reference surface with micron precision. For small lenses this is an important feature.

When the lenses are centered in their cells they may be held in place using cements or with centering screws coming thru the barrel sides. Some lenses are held in place by putting shims between the metal and the edge of the lens. This sounds like going back to edge centering, but the difference is that it does not depend on the accurate centering of the edge of the lens and the centering of the lens can be checked while under the interferometer.

After the lenses are firmly held in the cells the thickness from the lens surfaces to the cell reference surfaces can be measured. Precision spacers may then be used to set the surface spacings to the design values. This step may not be necessary if the mounting rings are made accurately to insure that the lens is located in the cell at the design position.

Stacking the Lens Cells to Make a Centered Lens Assembly

Once the lenses are centered in the cells the next step is to stack the cells to form the lens assembly. As each lens is stacked it can be centered on the reference optical axis of the interferometer. As lenses are added more and more return images can be seen and more and more ways are available for placing the next lens on a true reference optical axis. It may be feasible to reach centers of curvature or the image blobs may interfere, causing circular fringes. All the fringe systems must be concentric in a perfectly centered system. One can also remove the focusing lens in the interferometer and some of the reflected beams will form interference rings which also must be concentric. With a laser as source, one can see multiple reflection images, which also must be centered. A further aid is to allow focusing of the eye piece over a wide range. When the stack is complete it can be cemented together or bolted together with rods between the top and bottom of the stack.

Conclusion

With modern optimization programs, high quality optical glasses and willingness to use new methods for centering and spacing lens systems, some truly remarkable lenses should be possible. At the moment it will be costly to develop the tools to manufacture lenses this way, but with use the learning curve should lead to economical high quality lenses. The aim in this proposed method of assembly is that the lenses and mounts are tested at each stage of the assembly and the final lens assembly ahould perform as calculated. The conventional lens assembly in a barrel has to be assembled and finally tested to see if the lenses ended up centered. The location of the lenses is an unknown so there is no way to correct the problem without taking the lens apart and measuring what can be measured and trying a new assembly. Every time a lens is taken apart there is danger of damage to the cells and the lenses. Lenses with tenth wave surfaces are not disposable items, if one is concerned with costs. A method of assembly which can be carried out in a clean environment, checking each part as it is assembled, may take a bit longer but if it results in a lens that performs as expected the final testing is simplified and there is no need to run the risk of disassembling it.

Acknowledgments

The authors wish to acknowledge that many of the suggestions presented above were generated from experience gained at Tropel, and from common interests with John Buzzawa and James Anderson.

References

1. Yaeli, Joseph M., Optical Engineering vol 19 #3 June 1980

2. Hopkins, R. E., Applied Optics and Optical Engineering
Editors, Shannon & Wyant, Vol. VIII, Academic Press, 1980