New approach to optical assembly and cementing

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ABSTRACT

A novel method of projecting a reference axis in space for use in optical assembly of centered elements such as assembly in a barrel or in cementing multi-element lenses is presented. An axicon grating, a set of concentric, uniformly spaced circles, when illuminated with a point source of light creates a line of bright spots surrounded by concentric rings in both transmission through, and reflection from, the grating. This axis is easily interrogated with an autostigmatic microscope to gauge the distance a center of curvature, or other lens conjugate, lies from the axis created by the grating.

Keywords: Optical assembly, optical alignment, cementing doublets, autostigmatic microscope, computer generated hologram, axicon, PSM, Point Source Microscope

1. INTRODUCTION

We describe optical assembly and cementing of optical elements using an axicon plane grating to project an axis in space as a reference but the paper will be difficult to follow without reviewing the background and history of the axicon. First the idea of the axicon will be discussed and the reason for its invention, optical system alignment. Then it is shown how a plane grating with a simple pattern of equally spaced concentric circles behaves like a physical, glass, conical axicon, but that it is much easier to fabricate the grating as an essentially perfect axicon than making the conical axicon from a piece of glass or metal.

From there the properties of axicons are discussed to show why they are so useful in optical alignment, a step definitely needed for precision assembly and cementing. We refer to the literature to show that the reference axis can be created either by illuminating the axicon grating with a plane or spherical wavefront. Although the performance is nearly the same independent of the method of illumination it is important because it is so much easier (less expensive) to create a near perfect spherical wavefront with a bright point source of illumination than a large diameter, diffraction limited plane wavefront. Also, most of the literature about axicons assumes the illumination is by a plane wave giving the impression that this is the only way an axicon can be used to create an axis.

Along the way we will touch on Bessel beams, contrast a conventional laser beam with the axis created with an axicon grating and show why the axicon beam may be considered more precise than a laser beam when used for alignment during optical assembly. We will also discuss why axicons have not been used very much for precision assembly and cementing purposes in the past given that their use makes so much sense when looking at papers suggesting the use of axicons. Just before talking about alignment for assembly, we introduce the concept of an autocollimating flat with an axis. No longer does the flat define 3 degrees of freedom but 5 when it has an axicon grating printed on its surface.

From here we discuss the assembly of cemented doublets as a lead in to the assembly of more complex systems of refractive optics. While the discussion is meant to be complete it will be obvious that there are subtleties to the subject that bare further investigation. It should be obvious by the end of the paper that there are still many “what ifs?”.

2. HISTORY OF THE AXICON

In 1954, John McLeod of Eastman Kodak Company wrote a paper in JOSA titled “The Axicon: A New Type of Optical Element” where he said “The word axicon has been coined to cover a type of optics………[that have] the property that a point source on its axis of revolution is imaged to a range of points along its axis”.[1] McLeod credits van Heel[2] with prompting his research into the axicon. Van Heel’s diffraction methods had the precision McLeod was looking for but suffered from a lack of a sufficiently bright light source to make van Heel’s methods generally applicable.

Several points are made by McLeod about the glass axicons he had made; first the axicons made possible very precise angular measurement, slightly better than 1 μradian. Second, although very precise measurements could be made, good axicons were difficult to fabricate because they are extremely aspheric. Finally, reading between the lines, even though his axicons were an improvement on van Heel's methods relative to illumination, having a brighter light source would have made the axicon still more useful.

The final point McLeod makes in his paper will carry over directly to the discussion axicon gratings. When an axicon with a plane back is aluminized on either surface, and an autocollimating[3] or autostigmatic[4], microscope is used to view the reflected image along the axis of the axicon, "…the images will always be at unit magnification for any distance from the cone out to its maximum range. Moreover, the size of the diffraction pattern will always be constant. The illuminance will be inversely proportional to the first power of the distance, not to the usual second power. Because of this the angular diameter of the ring image remains constant…", an empirical observation about Bessel beam behavior before the theory was worked out.

In 1960 McLeod wrote a second paper[5], "Axicons and their Uses" that has a diagram which is a precise analog of the diagram we will show when we get to describing the alignment of refractive optics. The upper right of Figure 1 is a redrawn picture of Figure 4 from his paper with a pinhole source and a human observer looking into an eyepiece. In McLeod's black and white drawing it is not immediately clear that there are two bundles of light that will refocus back in the autostigmatic microscope, one bundle formed by the rays that hit the plane mirror at normal incidence and another by the rays creating the axis of the axicon. As the plane mirror is tilted away from being normal to the axicon axis the two spots will move away from the center of the eyepiece but at different rates depending on the axicon cone angle and the distance to the plane mirror. This is the same behavior we will see below with the axicon grating and a Point Source Microscope[6], a modern version of the autostigmatic microscope.

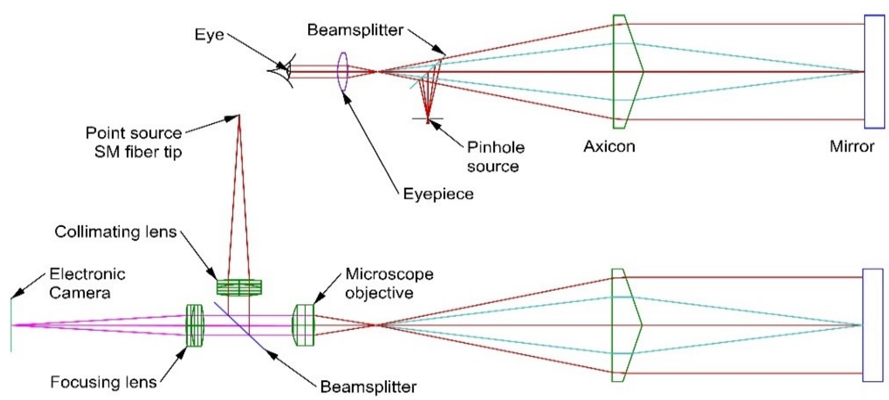


Figure 1. In the upper right is a redrawn version of Fig. 4 in from McLeod, Ref. 3. The lower part of the Figure shows the axicon and mirror viewed with an autostigmatic microscope to show that the optics of the two versions are analogues with the modern version having a brighter source and more sensitive detector.

As McLeod described many possible uses of the axicon he concluded that it was hard to say where this technique for alignment would lead but suggested that a machine tool could be guided photo-electrically along the axicon axis beam rather than using steel ways, the usual method of governing machine tool motion. This method would potentially permit a level of way straightness that could not be achieved with steel ways. In the very last paragraph, however, he said the real problem with this method was "light flux". The same year as McLeod published this second paper, Javan, Bennett and Harriott[7] first demonstrated a CW, HeNe laser and light flux would no longer be a problem.

3. AXICON GRATING

Now that the historical aspects of axicons have been introduced and how they are useful for alignment, we turn to axicon gratings. These grating are nothing more than a set of evenly spaced concentric circles printed on with chrome to, or etched into, a glass substrate using e-beam lithography. In the case of the gratings described here we have used both chrome on fused silica photomask substrates, and etched phase gratings on fused silica. The phase gratings are more efficient for use with refractive optics alignment while the chrome on glass seem better suited for aligning reflective optics in double pass setups. An example of a 75 mm square chrome on fused silica photomask grating with 20 µm line spacing is shown in Fig. 2. The 20 µm line spacing along with the 0.64 µm illumination gives a grating angle of 0.032 radians or about 2°.

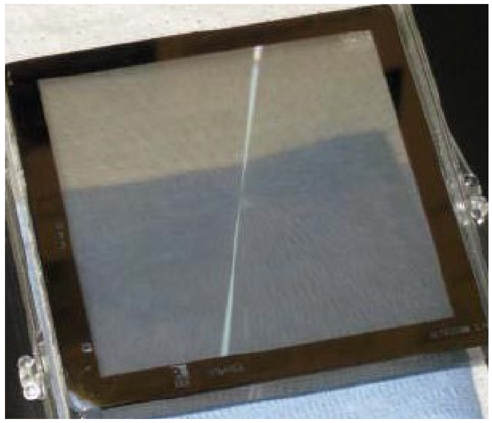


Figure 2. Chrome on fused silica photomask substrate 75 mm square with 20 µm line spacing axicon grating of evenly spaced concentric circles giving a grating angle of about 2°.

When the axicon grating is illuminated on or near its axis by the point source from an autostigmatic microscope, a Point Source Microscope (PSM) in this case, the reflected image looks like that shown in Fig 3, a bright central spot with increasingly dimmer concentric circles. Fig. 3 was cropped to show only the central 20% or so of the ~1 Mp frame.

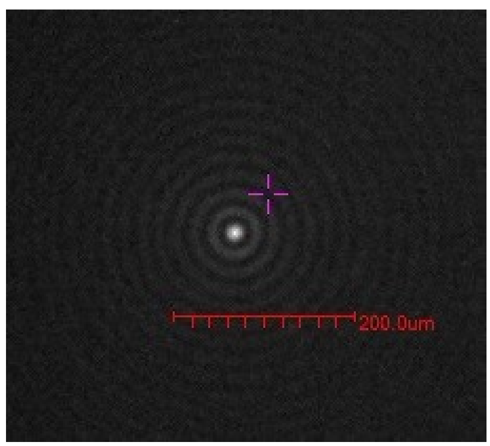


Figure 3. Reflected image from the grating in Fig. 2 where the autostigmatic microscope focus was close to the axis of the grating laterally and about 200 mm from the grating axially.

Because it is difficult to judge intensities from a grey scale picture, a trace was made through the central maximum in Fig. 3 to make the plot in Fig. 4. Here the camera had been adjusted so the exposure was just under the 8 bit linear range to avoid saturation. The full width, half max of the central peak is about 7 pixels and the first ring around the peak has an intensity of about 25% of the peak. The pixels are about 1 µm in object space and the centroid of the peak can be located to a couple tenths of a micrometer when using a 10x microscope objective on the PSM.

While Figures 3 and 4 give a good feel for the reflected intensity perpendicular to the axis of the reflected spot, they give no feel to the intensity axially. Most of the literature (excluding astronomical and light trapping uses of axicons and Bessels beams) concerns the intensity when the axicon is illuminated with a plane wave. There is, however, a thorough paper by Dong and Pu[8] that calculates the intensity variation along the axis of the grating when illuminated by a point source and contrasts that with the case for plane wave illumination. Figure 5 is taken from their paper where the red curve is the intensity for plane wave illumination while the blue is for a diverging spherical wavefront, or point source, illumination.

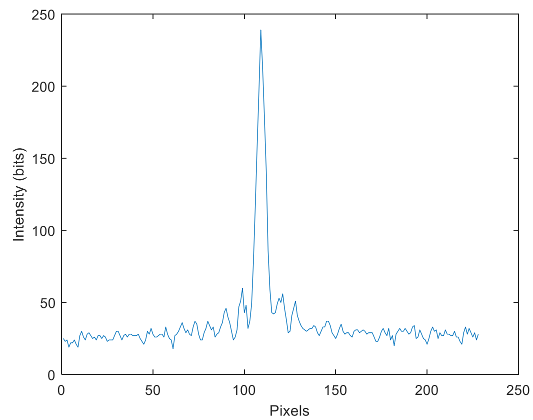


Figure 4. Plot of intensity through the central maximum in Fig 3 to show the width of the reflected image.

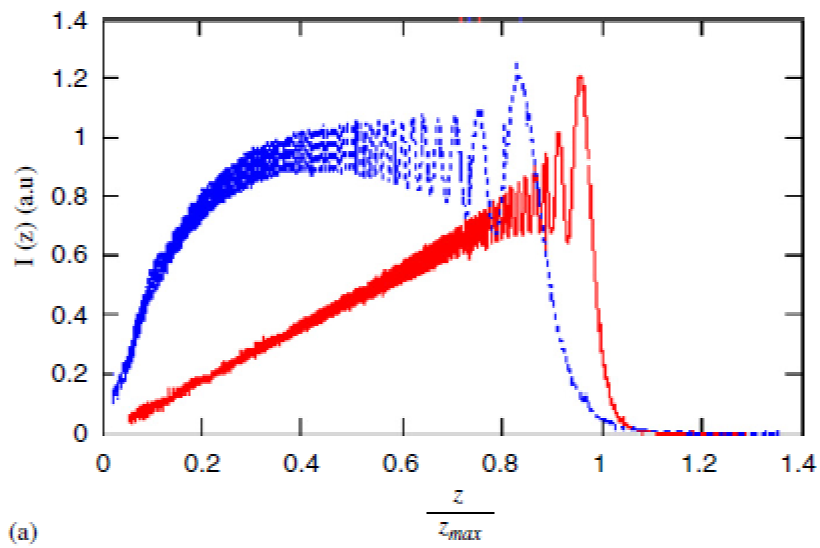


Figure 5. Intensity versus axial distance from an axicon for the axial image in normalized coordinates where the red curve is for plane wave illumination and the blue for a diverging spherical wavefront, that is, point source illumination. (This is Fig. 3a from reference 5, Dong and Pu.)

The abscissa in Figure 5 is normalized but for our case the 20 µm line spacing and 75 mm substrate gives the axicon grating a maximum useful radius of about 45 mm. This coupled with plane wave illumination gives $z_{max} = (45*d)/\lambda = (45*20)/0.64 = 1406$ mm for the region where the diffraction free or Bessel beam exists[9,10]. Figure 5 also shows the behavior that McLeod observed that the intensity of the image increases though oscillates with distance from the grating until z_{max} is reached whether plane or spherical wave illumination. With spherical illumination the increase is non-linear and reaches a maximum quicker than plane wave illumination. Reference 10 goes into this is more detail and gives a good review of so called Bessel beams and their uses outside the realm of alignment.

4. BESSEL AND GAUSSIAN LASER BEAM PROPAGATION

Since we are talking about alignment one might reasonably ask why not just use a HeNe laser beam and a quad cell, for example, instead of creating a Bessel beam. Even though the laser beam will be larger in diameter than the Bessel beam this really does not matter if one uses a nulling technique such as a quad cell and you do not have the fall off in intensity at z_{max}, the laser beam just keeps going.

From a practical viewpoint many alignment tasks are most easily implemented in a double pass arrangement and here it is difficult to incorporate the laser though certainly not impossible. A more important concern is with air turbulence. A laser beam travels through a volume of air that is nearly constant in diameter of a few mm. The Bessel beam is formed by light rays that travel through a substantial volume of air until the final focus and the fluctuations in the position of the image are substantially reduced by the effective averaging over the volume compared with transverse fluctuations in a collimated laser beam. This robustness to air turbulence is also borne out by recent research.[11]

5. AXICON GRATING ILLUMINATED WITH A POINT SOURCE

When an axicon grating (AG) is illuminated with a point source of quasi-monochromatic light centered on the grating pattern the light transmitted through the grating will form a line of bright spots beyond the grating defined by the location of the point source and the center of the grating pattern, see Figure 6. The bright spot varies in intensity as the viewing point is moved along the line, or axis, as was seen in Figure 5. The bright the spot is surrounded by uniformly spaced concentric rings whose intensity falls off with distance from the central bright spot as was seen in Figures 3 and 4. If the point source is moved too far off the axis of the grating the central spot becomes a more complex pattern[12] but in most practical cases of alignment this is never a problem.

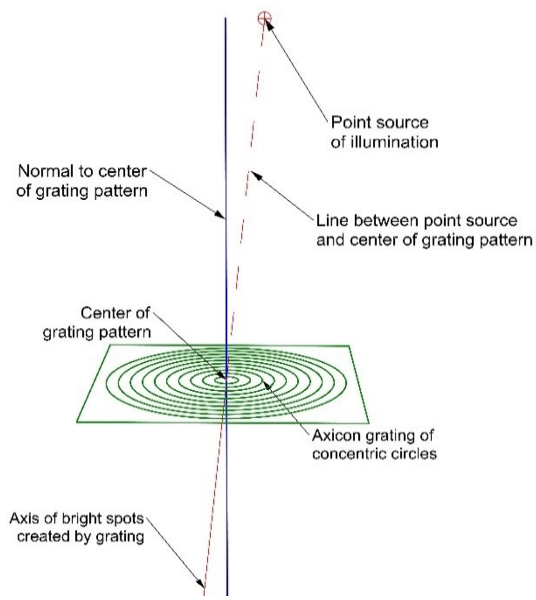


Figure 6. Axicon grating with point source displaced from the line normal to and through the center of the pattern. The axis of bright spots formed lies on the line joining the point source and pattern center.

The AG may also be used in reflection where two axes are formed, each axis defined by the point source of illumination and the center of the pattern of circles on the grating as seen in Figure 7. One axis is transmitted through the grating as previously described and is a continuation of the line defined by the illuminating point source and the center of the pattern. The other axis is a mirror image of the first axis in the plane containing the first axis, that is, the second axis is mirrored about the center on the grating pattern. The second axis starts at the center of the pattern and reflects back in the direction of the illuminating point source but on the other side of the normal to the center of the grating pattern.

A final word about the axicon grating before proceeding on to its use for alignment during assembly and cementing. Since the grating can be printed on a photomask substrate with a flatness of λ/4 or better, the axicon grating can be thought of as an autocollimating flat with an axis. This means that the grating not only defines 2 angular degrees of freedom and a distance along its axis, but 2 additional degrees of freedom perpendicular to its axis. For rotationally symmetric optical systems this completely defines all the necessary degrees of freedom for alignment.

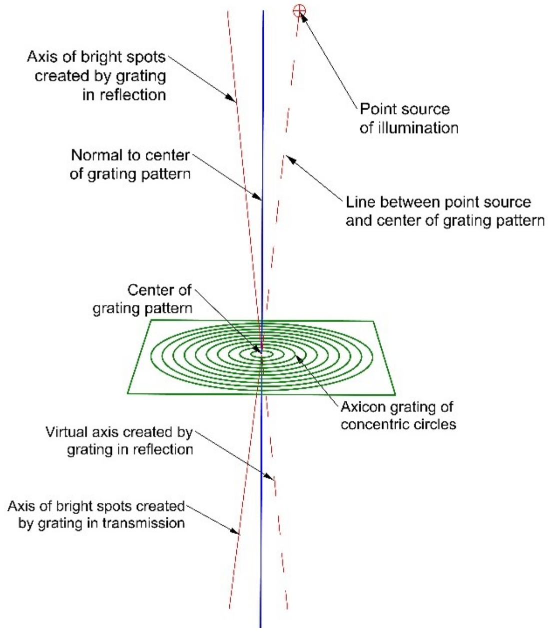


Figure 7. Axicon grating used in reflection with the point source displaced from the line normal to and through the center of the pattern. The axis of bright spots formed in reflection lies on a mirror image of the line joining the point source and pattern center.

6. AUTOSTIGMATIC MICROSCOPES

Since the experimental work here was carried out using a contemporary autostigmatic microscope, the Point Source Microscope (PSM), it is worthwhile looking at how the optics of the microscope work for a full understanding of performing alignment with an autostigmatic microscope (ASM). An autostigmatic microscope[4] has a point source of light directed at an objective lens through a beamsplitter such that the objective lens produces an image of the point source and the wavefront from that image continues on expanding in space as a nearly perfect spherical wavefront.

If a specular surface is placed at the focus of the objective, light is reflected back into the ASM and forms an image (a Cat's eye image) in the object plane of an eyepiece or on an electronic detector. The reflected spot image is precisely conjugate laterally with the point source creating the image so that if a crosshair in the eyepiece is adjusted to be coincident with the reflected image, the crosshair shows the precise lateral position of the focused spot exiting the objective as shown in Figure 8. In other words, when looking into the eyepiece, the center of the crosshair is precisely conjugate with the objective focus and, consequently, the point source creating the focused spot. In an ASM with an electronic detector, the electronic crosshairs are centroided with an algorithm so they are precisely centered on the Cat's eye image on the detector. When the crosshairs are centered on the Cat's eye image, the outgoing focus is precisely conjugate with the point source and the crosshairs in the eyepiece or on the detector.

Now if the focus of the objective of the ASM is placed near the center of curvature of a concave sphere, the reflected light will form a spot on the detector that, in general, will be shifted from the center of the crosshairs as shown in Fig. 9. The distance of the reflected spot from the crosshairs will be exactly twice the distance the ASM focus is shifted laterally from the center of curvature of the sphere times the magnification of the ASM. Since the radius of the sphere is known, or can easily be measured, the distance between the reflected spot and the crosshairs also gives the angular error, or tilt of the spherical surface, relative to a line between the ASM focus and center of the aperture of the sphere.

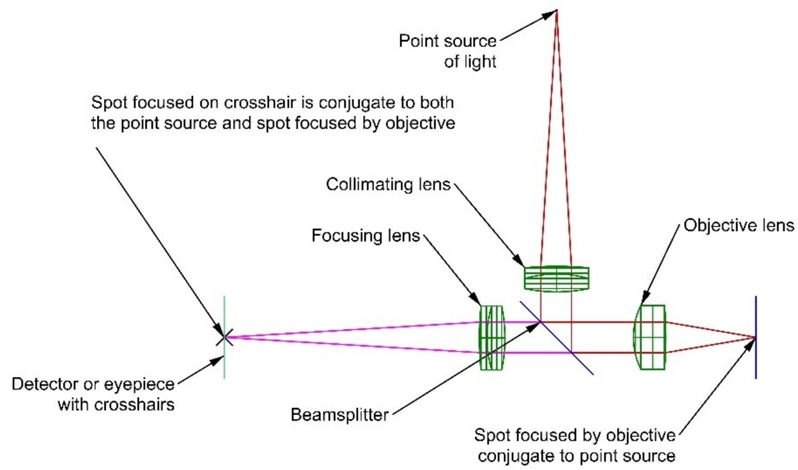


Figure 8. An autostigmatic microscope (ASM) focused on a specular surface to produce a Cat's eye image on the detector conjugate to the illuminating point source as a means of positioning reference crosshairs.

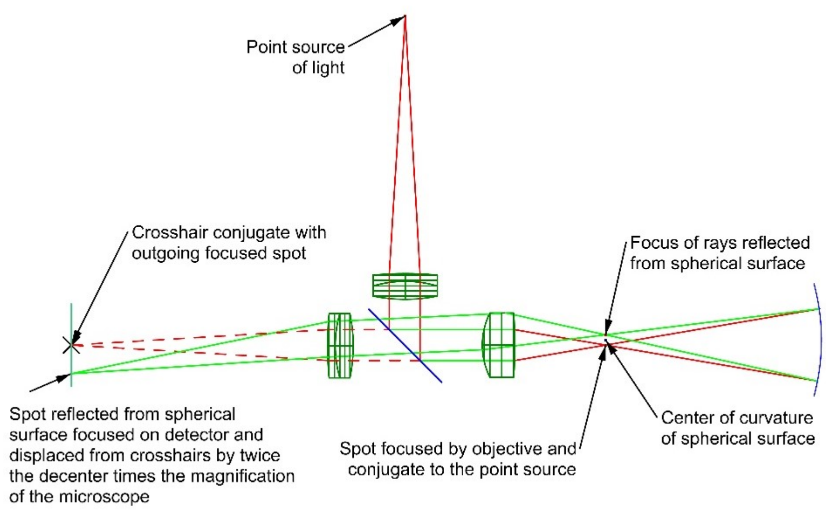


Figure 9. Autostigmatic microscope near the center of curvature of a concave spherical surface. The reflected focus is a distance of twice the decenter of the center of curvature from the out-going focused spot and falls on the detector at a distance from the crosshairs of twice the decenter times the AM magnification

7. CENTERING WITH THE ASM AND AXICON GRATING

With this background on both the AG and the ASM, consider centering a meniscus lens using the two. Assume the meniscus for a cemented doublet is placed between the autostigmatic microscope and the grating with the concave surface facing the microscope. The ASM is set axially so that the distance of its objective focus from the concave surface is just the radius of curvature of the surface so the focus of the microscope objective will be at the center of curvature of the concave surface once the meniscus is inserted in the setup as in Figure 10. It is assumed there is a seat in the setup for the meniscus to sit on so we know explicitly where the center of curvature will lie when the meniscus is inserted.

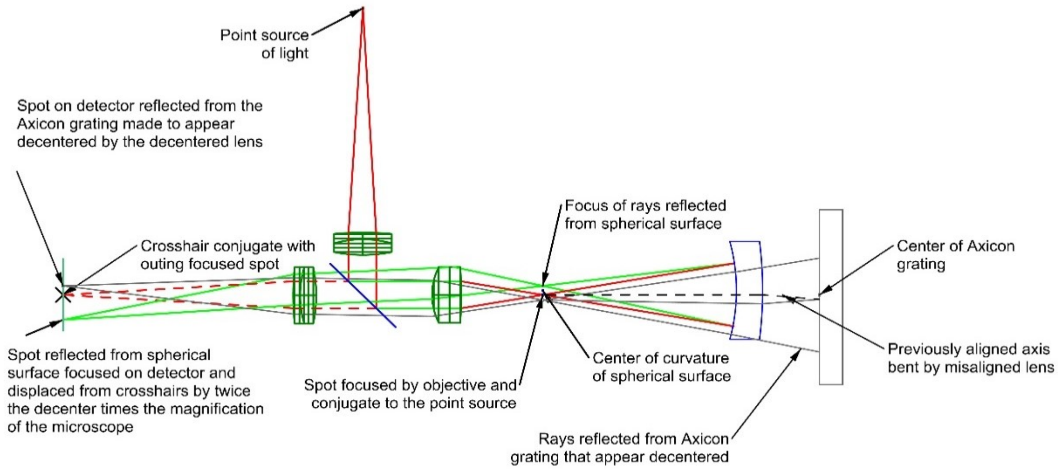


Figure 10. Decentered lens inserted between the AM and the AG. Two focused spots are seen on the detector, one from the center of curvature of the lens and one from the reflection from the AG as seen through the lens.

Then the ASM is centered laterally so the reflected spot from the AG is centered on the crosshairs. (It is assumed the crosshairs have previously been centered using a Cat's eye image off of a surface.) This lateral centering assures the focus of the ASM lies on the axis of the AG because the illuminating spot of light from the ASM is coincident with the reflected spot from the AG as illustrated in Figure 7.

At this point the focus of the ASM has been located in three degrees of freedom to where the center of curvature of the concave side of the meniscus should lie when it is inserted in the setup and is perfectly aligned. Of course, in general, the centers of curvature of neither side will not lie on the axis of the grating when the meniscus is inserted.

When the meniscus lens is introduced in the set up, two reflected spots will be visible on the detector, one from the center of curvature of the concave surface and the other from light transmitted through the lens from the ASM, reflected off the AG and returned back through the lens into the ASM as shown in Fig. 10. To achieve centering the lens must be decentered and tilted until both spots are again centered on the crosshairs. It is not sufficient that the two spots are coincident, they must also be centered on the crosshairs so that looking at the detector screen it appears just as it did prior to inserting the lens, an apparent single spot centered on the crosshairs.

When the two spots are both centered on the crosshairs, both centers of curvature of the lens lie on the axis of the grating and the both surfaces of the lens are normal to the axis of the AG at the point where the axis passes through the lens, that is, there is neither decenter nor tilt of the lens relative to the axicon grating. Since both spots are centered on the crosshairs the lens is aligned such that the light transmitted through the lens is undeviated so the alignment relative to the axis of the AG is the same as before the lens was introduced.

It is clear that once the lens is centered the axis from the grating will be in exactly the same place it was before the lens was introduced. This means that if subsequent lens elements are to be aligned to the first, the procedure is repeated by first moving the ASM axially to the center of curvature of another concave surface or the back focus of the assembly. Then the ASM is realigned laterally until the reflected spot from the grating is centered on the crosshairs. This re-alignment is necessary because it is assumed the axial stage is not perfect causing lateral misalignment of the ASM when it is moved axially. Once the ASM is re-aligned laterally the next element can be introduced. In general two spots will be seen and the lens will have to be aligned in tilt and decenter just as the first initial was until both spots lie centered on the crosshairs.

8. A PRACTICAL VERSION OF LENS CNETERING

To this point in the discussion the meniscus, or for that matter, the first element in any assembly, has been shown floating in space. In this section we describe a practical mechanism for locating and holding this first element using a simple vacuum chuck. Looking at Figure 11 where we have turned the set up vertical so that we can use gravity to best effect, the AG is set on a base plate with the grating pattern down.

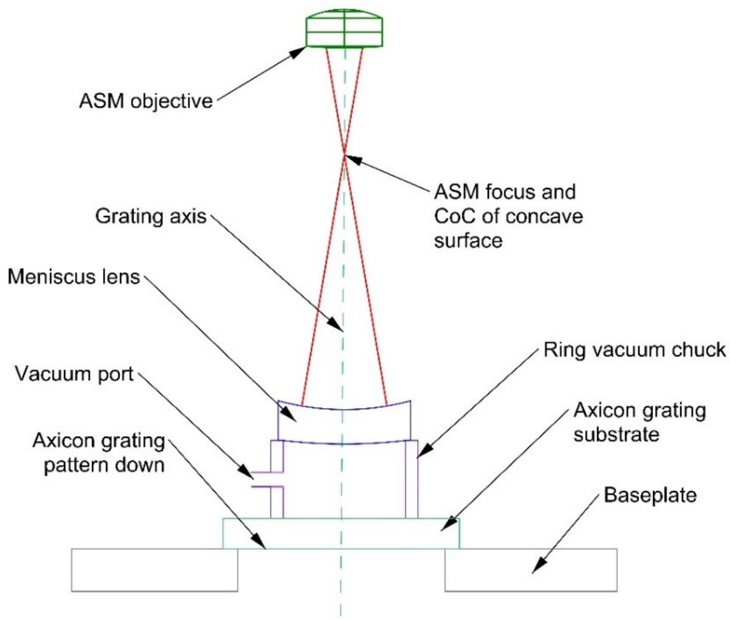


Figure 11. A practical version of lens centering incorporating a vacuum chuck to secure the lens during alignment

A ring shaped fixture serves as part of the vacuum chuck and mount for the convex side of the meniscus. The metal ring, with a protective covering on its lower surface to prevent scratching the grating substrate, sits directly on the rear side of the grating which also serves as the bottom part of the vacuum chuck. Once the lens is set on the ring the cavity in the ring is sealed and a vacuum can be drawn. Because the dimensions of all the mechanical components in a particular setup are known it is possible to calculate the precise axial position of the ASM focus relative to the center of curvature of the concave surface of the meniscus lens to achieve the correct axial spacing.

When the ASM is aligned axially and laterally at the center of curvature of the meniscus lens, the lens is placed on the vacuum chuck and a mild vacuum drawn to lightly clamp the lens in place. In general, the situation will now be as in Fig. 10 where the centers of curvature of neither side of the lens lie on the axis of the AG, and two spots will appear on the ASM video screen, one a reflection from the center of curvature and the other from the projected grating axis. Now the vacuum chuck ring is gently nudged across the grating substrate to correct decenter while the edge of the lens is tapped to make it tilt about the center of curvature of the convex side to correct tilt. By a succession of minor adjustments to the vacuum chuck ring and tilt of the lens the two spots are brought together and centered on the crosshairs of the ASM. The ASM screen will now appear just as it did prior to introducing the lens because the projected axis from the grating is again aligned precisely with the ASM.

A number of items should be reviewed at this point. First, the lens is truly centered because the optical axis of the lens is the line joining the centers of curvature and one of those centers now lies on the axis of the ASM. The definition of optical axis implies that the axis is normal to both lens surfaces and thus light traveling along the optical axis will be undeviated when passing through the lens. Since the grating axis projected through the lens also lies on the axis of the ASM, the optical axis of the lens must be coincident with the grating axis. It should be emphasized that in order to accomplish this alignment there must be the ability to both tilt and decenter the lens during the alignment process.

Next it is noted that the alignment of the lens was accomplished without having to move the ASM axially during the alignment to go from one center of curvature to the other. Nor was it necessary to use two ASMs to monitor both centers of curvature as suggested in a prior paper by the author.[13] The absence of a need for axial adjustment makes the alignment particularly simple because the person doing the alignment only has to be concerned with getting the two light spots centered on the crosshairs. No other operations are needed with the exception of increasing the vacuum to lock the lens in place once alignment to the required tolerance has been achieved.

Further, the method illustrated has a simple way of holding and clamping the lens once it is aligned that also serves as part of the alignment apparatus. The vacuum chuck serves as the method of moving the lens laterally to achieve the centration part of the alignment. In fact, in the most practical way of setting up for alignment of several lenses of the same kind, as would be the case for cementing a lot of doublets, stops could be located to keep the vacuum chuck located in its nominal lateral position so only the slightest adjustment of decenter would be needed during the adjustment of tilt. This would make the centering go quite rapidly since only the slightest decenter would be needed from the nominal position.

Finally, and this may be the most practical aspect of the method, the method is universal, that is, no addition parts are needed in the set up for a different lens radius or back focus other than adjusting the axial height of the ASM. The one thing that would need changing is the inner diameter of the vacuum chuck if the new lens had a different clear aperture than the original lens. Otherwise, the alignment setup is completely universal as opposed to methods suggested in a second previous paper by the author.[14]

9. A SECOND PRACTICAL MATTER, LIGHT SOURCES

The procedure outlined to this point works perfectly in theory but not as well in practice because the light reflected from the AG is less intense than the light reflected from a confocal conjugate of the assembly such as a center of curvature or back focus. This means that with the single source in the ASM the brightness of the two spots on the detector will not be optimum. In general, one of the spots will be too dim to be useful relative to the other. It is much better to have a second, adjustable intensity light source behind the AG.

As discussed earlier, the AG works both in reflection and transmission. By placing a single mode fiber source on the far side of the AG, an axis is created that can be viewed in the ASM on the other side as was shown in Figure 6. The axis created this way is the line between the source and the center of the axicon pattern. The ASM is first used to assure the fiber source is located precisely on the axis of the grating by first aligning the ASM laterally to the AG with the source behind the grating turned off. When the ASM is aligned with the grating axis the reflected spot will be centered on the ASM crosshairs. Now the spot created by the source behind the grating must also be centered on the crosshairs by moving the source laterally until the spot it creates also lies on the crosshairs of the ASM.

The second source also helps with this initial alignment because the PSM electronically centroids on the spots on the detector. By being able to operate the two light sources independently, one source at a time can be centered on the crosshairs using the electronic centroid position feedback. This is a more precise way of aligning the two spots because once the spots are coincident, or nearly coincident, it is impossible to improve on the alignment because it is not obvious which spot is being viewed. By turning on one spot at a time it is clear how close each spot centroid is to the center of the crosshairs.

10. CEMENTING A DOUBLET

In Section 8 we explained how the meniscus half of a doublet is aligned to the reference axis produced by the AG. Now consider adding the crown half. The ASM could be moved axially to either the concave half of the meniscus as viewed through the crown, or moved to the back focus of the assembled doublet. It is generally preferable to move to the back focus because this gives a larger optical lever arm than the center of curvature of the meniscus and for a similar centroiding sensitivity in either case, the longer arm will lead to better angular alignment.

The ASM is moved axially to the back focus of the assembled doublet where the plane surface of the grating substrate is used as the autocollimating plane mirror. As the ASM is moved axially the reference axis projected through the lens will appear to drift off the ASM crosshairs unless the vertical stage is very precise and perfectly aligned to the grating axis, something that is not probable to the µm level nor necessary. Rather, once the ASM is at the correct axial position to view the back focus of the assembled doublet, the ASM is moved laterally until the axis is again centered on the cross hairs.

Now the positive element is introduced on top of a drop of cement. Since the concave surface of the meniscus was already aligned, the mating convex surface should be perfectly aligned as long as there is no wedge in the cement. The positive element is then aligned perfectly when the single return spot from the back focus lies centered on the crosshairs. To check if there is cement wedge, the ASM is adjusted axially until it is at the center of curvature of the concave surface of the meniscus as viewed though the positive element. If there is wedge in the cement, two spots appear in the ASM, one from each surface with matching radii. The wedge can be worked out until there is a single spot and then the ASM moved back to the back focus. Notice in this case there is no need to center the ASM because the concave surface of the meniscus has not moved. All that is needed is to work the positive element to remove wedge until the two spots coincide.

If the stage is repeatable, and no lateral adjustment were made to the ASM, and positive element can be centered by looking at the back focus and adjusting the spot to the ASM crosshairs. If there is a question about the lateral adjustment, the assembled lens can be removed from the vacuum chuck, the ASM re-centered and the lens replaced on the vacuum chuck and re-centered. Since it is difficult to re-introduce wedge in the cement the lens can be aligned by getting both spots centered on the ASM crosshairs.

11. ASSEMBLING LENSES IN A BARREL

Assembling lens elements in a barrel or cell is not much different than cementing a doublet assuming the barrel can be used as part of the vacuum chuck as shown in Fig. 12. Here a vacuum chuck is made that will interface with the front of the cell so that when the first element is placed on its seat the element closes the vacuum chamber. Adjustment screws are used to center the cell to remove decenter from the lens while adjustment screws in the cell tilt the lens on its seat to remove tilt. Centering the first element is a combination of centering the seat by translating the cell perpendicular to its axis and using the adjustment screws to remove tilt. Once the lens is centered and free of tilt it is cemented in place and the adjustment screws can be removed.

As opposed to centering the first element in cementing a doublet, it is most often the case that the element is positive and the back focus of the element is easily accessed. This is the case for the example in Fig. 12. The AG is used not only to create an axis in space but also to act as the autocollimating plane mirror for accessing the back focus of the lens. The reflection from the grating is relatively efficient compared to the spots defining the axis so there is no trouble finding the back focus of the lens. Of course, if the first element is negative it can still be centered using a center of curvature just as the meniscus was in the preceding section.

Once the first element is secured in the cell, this combination of cell and lens becomes the reference for the remaining lenses. The vacuum is not released until the whole assembly is complete since the first element and cell define the axis for all subsequent lens elements. Now, however, there must be a means of both tilting and decentering the next elements. This can be accomplished using a slightly undersized spacer so that it may be adjusted to center the lens seat while the lens is tilted as shown in Fig, 13.

We have previously mentioned that using the AG to create a reference axis to align to rather than using the axis created by a rotary table makes the process of centering and assembly less complex. In addition, it greatly simplifies the use of a vacuum chuck for no rotary vacuum feedthrough or additional vacuum channels in the air bearing are needed to get the vacuum to the chuck. A simple flexible hose is all that is needed.

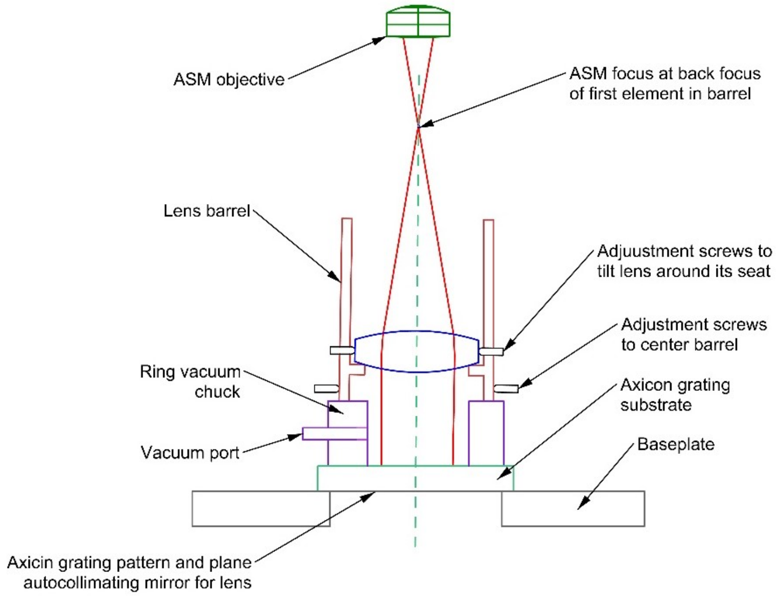


Figure 12. Assembling and centering the first element in a lens barrel

As with the first lens, two spots will be seen in the ASM, one from the source behind the grating and the other from the back focus of the assembly of two elements. Again, a process of tilting and decentering the second element will move the spots to be coincident and centered on the crosshairs of the ASM. If the assembly has a negative efl then a center of curvature of the second element can be used for centering. The adjustment screws shown in Fig. 13 permit this adjustment assuming there is clearance so the spacer may be moved slightly within the cell. Also, it is wise within practical limits of the optical design, to use the longest conjugate for each lens in the assembly to give the greatest angular sensitivity to the adjustments.

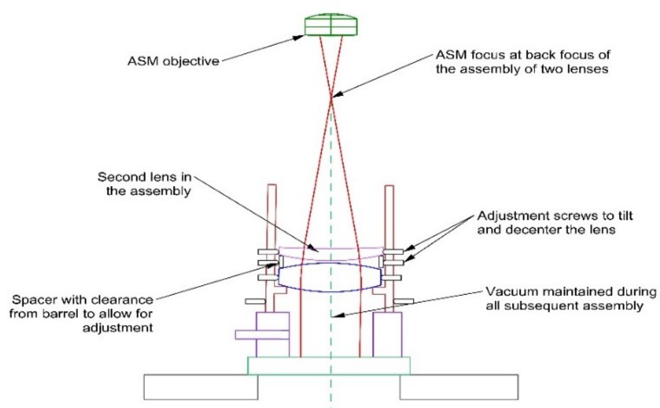
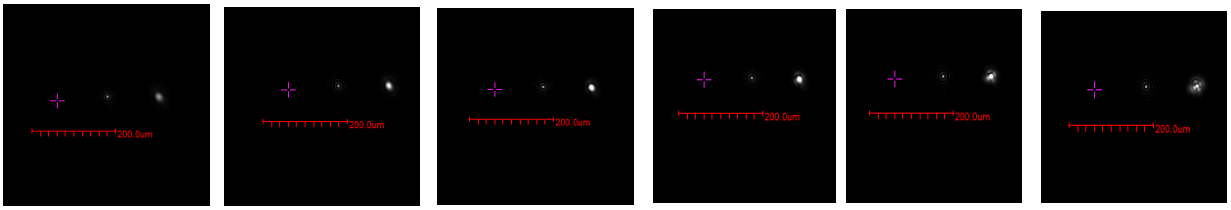


Figure 13. Lens barrel with second lens inserted

12. EXAMPLES OF SPOT MOVEMENT DURING CENTERING

In this final section we give a couple of examples of what the spots look like during alignment. A 150 mm efl singlet was used with a 25 mm diameter. The setup was similar to that shown in Fig. 12 in terms of the location of the AG lens and ASM. In this case the element could be moved axially and and laterally. In Fig. 14 the element was moved axially in 100 µm steps through best focus with the ASM at the back focus of the element.

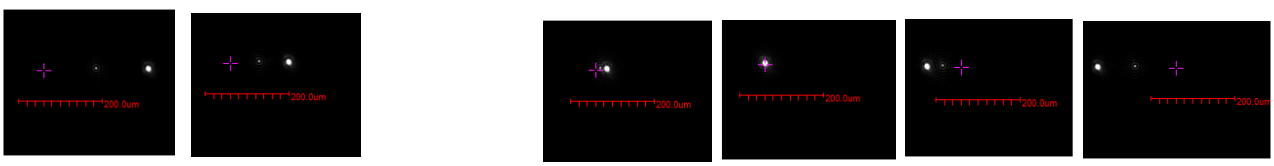


250 150 50 -50 -150 -250

Figure 14. Decentered 150 mm efl lens as the ASM was moved through focus in 100 µm steps.

The lens had been well centered but was purposefully decentered to separtate the transmitted spot, the one closest to the crosshairs, and the spot from the back focus. The lens was moved through best focus from outside to inside focus on the right in 100 µm steps. As seen, the axial motion does not move the spots laterally but the double pass spot on the right of each picture is clearly out of focus at either ends of the travel. In fact, at the µm level the spots do move do to the lack of perfect straightness of the was in the stage. This small motion could be seen in the centroid data on the screen of the PSM.

Next the stage was translated laterally in 50 µm steps as shown in Fig. 15 where the starting position was that in Fig. 14. As is easily seen the double pass spot moves twice as rapidly as the single pass spot and that at a total motion of 162 µm from the start the spot are coincident and behind the cross hair. (The image at 100 µm was inadvertantly not saved.)



0 50 100 150 160.2 200 250

Figure 15. Lens decentered in 50 µm steps starting from position in Figure 14.

When the spots were centered they were behind the crosshairs. Since the spot produced in reflection by the PSM is double pass off the grating it moves twice as far from the cross hairs as the spot created by the grating and is single pass through the system.

Although it is almost impossible to read off the Figure, the double pass spot moved the expected 100 µm and the single pass spot half of that. Also, tilt had little effect on the centering as would be expected for a relatively slow, thin lens, but it was not possible to align the lens using decenter alone. It was just much more sensitive to decenter.

13. CONCLUSION

A method of precision centering has been presented that eliminates the need for a rotary table to establish a reference axis in space to align to. Rather the reference axis is created with an axicon grating and all the alignment can be done where the components are stationary and both tilt and decenter are adjusted one element at a time. This greatly reduces the complexity and cost of either precision cementing or centering. By eliminating the rotary table it also makes possible the simple use of vacuum to fixture the lens elements as an assembly is being put together. This is a clean method of fixturing parts where the clamping pressure is easily controlled; a mild vacuum to clamp during alignment and a hard vacuum to hold components firmly in place during subsequent steps in the assembly process.

The complexity of the centering process itself is simplified because all the components are stationary, and the centering sensor, an autostigmatic microscope does not have to be moved during the centering of any one element. The operator can concentrate simply on that one element and complete the centering in a non-rotating coordinate system so there is easy hand-eye coordination of the moves to tilt and decenter the lens to accomplish precision centering. Further, during cementing, the method permits an easy check for wedge in the cement layer and gives an easy way to check the wedge is eliminated. The method described is less expensive in terms of hardware needed, easier to maintain over the long run and the alignment itself it easier to perform with the consequence of increasing productivity.

REFERENCES

[1] McLeod, J. H., “The Axicon: A New Type of Optical Element”, JOSA, 44, 592-7 (1954).
[2] van Heel, A. C. S., “High Precision Measurements with Simple Equipment”, JOSA, 40, 809-16 (1950).
[3] Smith, W., [Modern Optical Engineering], 3rd ed., McGraw-Hill, New York, xxxxx
[4] Drysdale, C. V., “On a simple direct method of determining the curvatures of small lenses”, Trans. Opt. Soc. 2, 1 (1900) London, https://doi.org/10.1088/1475-4878/2/1/301.
[5] McLeod, J. H., “Axicons and Their Uses”, JOSA, 50, 166-9, (1960).
[6] Parks, R. E., “Autostigmatic microscope and how it works”, Appl. Opts., 54, 1436-8 (2015).
[7] Javan, A., Bennett, Jr., W. R. and Herriott, D. R., “Population Inversion and Continuous Optical Maser Oscillation in a Gas Discharge Containing a He-Ne Mixture”, Phys. Rev. Lett. **6**, 106 (1961).
[8] Dong, M. and Pu, J., “On-axis irradiance distribution of axicons illuminated by spherical wave” Opt. Laser Technol., 39, 1258-61 (2007).
[9] Durnin, J., “Exact solutions for nondiffracting beams. I. The scalar theory”, JOSA-A, 4, 651-4 (1987).
[10] McGloin, D. and Dholakia, K., ‘Bessel Beams: Diffraction in a new light”, Contemporary Physics, 46:1, 15-28, (2005).
[11] Nelson, W., Palastro, J. P., Davis, C. C. and Sprangle, P., “Propagation of Bessel and Airy beams through atmospheric turbulence”, JOSA-A, 31, 603-9 (2014).
[12] Zhao Bin and Li Zhu, "Diffraction property of an axicon in oblique illumination," Appl. Opt. 37, 2563-2568 (1998).
[13] Parks, R. E., “Lens centering using the Point Source Mircoscope”, Proc. SPIE, 6676, 667603 (2007).
[14] Parks, R. E., “Optical alignment using a CGH and an autostigmatic microscope”, Proc. SPIE, 10377, 103770B (2017).