# Optical alignment using a CGH and an autostigmatic microscope

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## ABSTRACT

We show how custom computer generated holograms (CGH) are used along with an autostigmatic microscope (ASM) to align both optical and mechanical components relative to the CGH. The patterns in the CGHs define points and lines in space when interrogated with the focus of the ASM. Once the ASM is aligned to the CGH, an optical or mechanical component such as a lens, a well-polished ball or a cylinder can be aligned to the ASM in 3 or 4 degrees of freedom and thus to the CGH. In this case we show how a CGH is used to make a fixture for cementing a doublet lens without the need for a rotary table or a precision vertical stage.

**Keywords:** Computer generated holograms, autostigmatic microscope, optical alignment, centering, testing singlet lens elements in transmission.

## 1. INTRODUCTION

We have previously reported on using computer generated holograms (CHGs) as fixtures for performing optical alignment[1], and simulated how they would be used. In this paper we report on the design, assembly and use of a CGH for the precision cementing of a doublet lens without the need of either a precision rotary table or a precision vertical stage to illustrate the idea of a practical use of a CGH for alignment purposes.

We begin by describing the origin of the insight that led to our exploring the idea of using CGH's as alignment tools and fixtures, and then move on to describe the specific application to precision cementing of lenses.

There are two generic methods of cementing doublets, and one is to center and edge the two component lenses separately to the same diameter and then center the lenses using their peripheries against a "V" block. The other is to leave the two elements oversized and un-centered, and then cement them using a rotary table and optical means for centering. The final step would then be to edge the cemented element to diameter while keeping the edged periphery co-axial with the optical axis. It is this second method of cementing is used for the most critical assembly of doublets and is the one discussed here.

## 2. ORIGIN OF THE IDEA OF USING CGH'S AS FIXTURES

We begin the discussion rather far from cementing lenses, but this background is needed to understand the method. The centering and cementing is a familiar step in optical fabrication, but the use of CGH's as fixtures is not and that is why we begin there.

From their earliest use as null optics for testing aspheres, CGH's had to be precisely aligned to the interferometer transmission sphere used for testing the asphere. This was originally done by attaching balls to the corners of the CGH's using the mechanical features of the substrate of the CGH's as datums. The balls then would mate with "V" grooves attached in some means to the transmission sphere to form a kinematic mount for the CGH.

More recently, Coyle[2] showed that the balls used for alignment could be attached to the CGH in a more precise way, and more importantly, one that was directly and physically related to the aspheric null test pattern by including Fresnel zone patterns that defined the locations of the centers of the alignment balls. Since the Fresnel zone patterns were written on the CGH substrate using the same program as the null design, and written as part of the overall pattern, the relative position of the null pattern and alignment patterns were precise to better than 200 nm on a 6" photomask substrate[3].

Coyle designed the Fresnel patterns on the CGH substrate so that when the pattern was illuminated with a collimated, monochromatic beam of light normal to the plane of the pattern, the pattern would focus the light at the center of the ball to be used for alignment, typically a ½" diameter steel ball that would then be cemented directly to the photomask substrate of the CGH. Coyle designed and built a special purpose collimator for use in positioning the balls and it worked as shown in Fig. 1. If the ball was not perfectly centered with respect to the Fresnel pattern the reflected light would appear decentered in the collimator. Once the ball was centered it was cemented to the substrate.

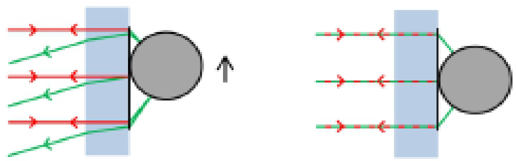

Fig. 1 Using a collimated beam to center a ball with respect to a Fresnel zone CGH pattern.
(Figure from L. Coyle Dissertation)

There are several other ways of implementing this scheme that do not require a special purpose tool. Either an autostigmatic microscope (ASM) incorporating a monochromatic light source or an interferometer can be used to position the balls with respect to their Fresnel zone alignment patterns from either side of the photomask substrate depending on how the radius of curvature of the Fresnel pattern is designed.

## 3. REFLECTED SPOT OR IMAGE OF THE FRESNEL ZONE PATTERN

Before discussing how to align balls to Fresnel zone patches it is useful to both see what the pattern looks like and what an ASM or a Fizeau interferometer sees when focused at the focus of the CGH pattern. Fig. 2a shows a microphotograph of a Fresnel pattern that focuses 5 mm above the CGH when illuminated by a point source 5mm above the pattern. There is a scale bar on the photo whose length is 200 μm.

Fig. 2b shows the reflected "spot" from the pattern as seen with an ASM, in the case, a Point Source Microscope (PSM)[4]. The word spot is in quotes because the cross shape to the spot was a purposeful artifact of the pattern design that included about a half wave of astigmatism. The lack of a true 90° cross is an artifact of squeezing the image so the whole scale bar could be included in the photo. The magenta crosshair that indicates the center of the PSM field of view also shows the effects of foreshortening. The return spot was not centered on the crosshair to better show the shape of the reflected spot.

Fig. 2c shows an interferogram taken with a Fizeau interferometer of the Fresnel pattern with a radius of 135 mm that was 28 mm in diameter on the CGH. Although no data was taken as to the actual sphericity of this wavefront it is clearly on the order of $\lambda/10$ P-V or better. The obscuration in the center of the interferogram is actually out of focus images of three concentric Fresnel patterns of shorter radii, 45, 15 and 5 mm. It is the 5 mm radius part of this pattern that is shown in Fig. 2a.

## 4. USE OF AN AUTOSTIGMATIC MICROSCOPE TO LOCATE ALIGNMENT BALLS

### 4.1 Aligning balls to a Fresnel zone pattern in theory

While we will address the question of locating the alignment balls on the CGH specifically, keep in mind the same principles apply for spherical surfaces of any radius, particularly the spherical surfaces of lenses located at any practical distance from the CGH substrate. The same applies to cylinders with specular surfaces.

Just as Fresnel zone patterns will focus collimated light to a point, similar Fresnel patterns will focus a point source of light back upon itself as shown in Fig. 2b. To create the alignment patterns for the balls to be cemented on the CGH, Fresnel patterns are designed to reflect a point source of light focused at a point equal to the ball's radius above the surface of the CGH. In this way, an ASM or interferometer focused at the Fresnel zone focus will also reflect light back from the surface of a ball centered on the pattern as though the light were coming from the center of the ball as shown in Fig. 3a and b. Also note that the Fresnel patterns produce a focused spot on the far side of the CGH due to the diffraction of the opposite order, and the two images create an axis for the CGH just as in the case of a lens.

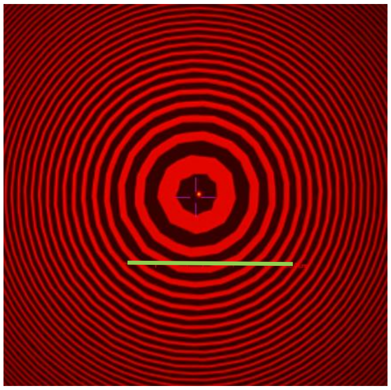

Fig 2a Microphotograph of a 5mm radius Fresnel pattern with a 200 mm scale bar (green)

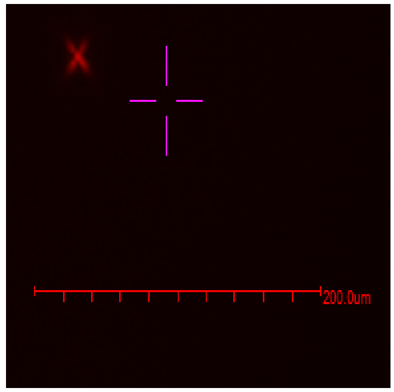


Fig. 2b Reflected spot image is the red cross, cross shape due astigmatism in pattern

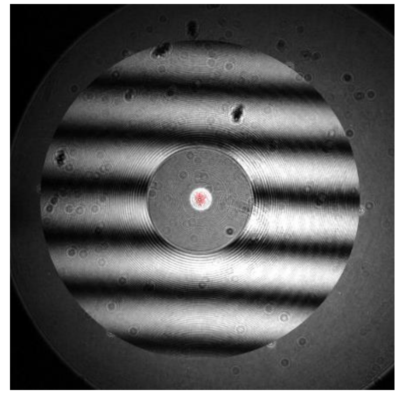

Fig. 2c Interferogram of 28 mm diameter Fresnel pattern with a radius of 135 mm

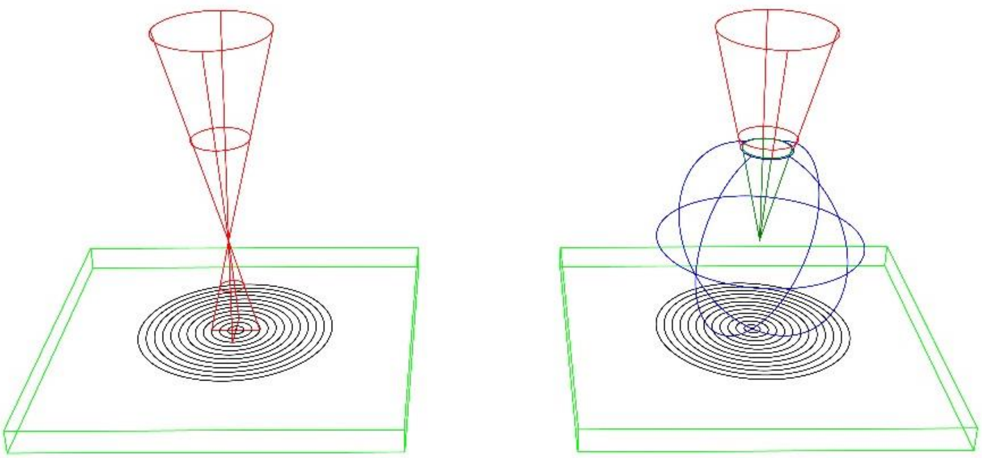

Fig. 3 ASM objective focused above the CGH (a) and a ball with its center at the ASM objective focus (b)

### 4.2 Aligning balls to Fresnel zone patterns in practice

To align the ball to the CGH pattern, the CGH is moved until the reflected spot is centered on the crosshairs in the ASM and then the ball is moved into place over the pattern until the reflection from its center is centered on the ASM crosshairs. With care, both operations can be done with precision of about 1 µm. Fig. 4 shows this operation of aligning a ball to its Fresnel pattern. The ball was held is the small set of pliers clamped with a rubber band. A combination of the ball and the two handles made a three point kinematic interface for a stable adjustment. The pliers were gently tapped to center the ball and then adhesive was applied to fix the ball. The pieces of tongue depressor were simply to catch a ball if one got away.

Although Fig. 4 shows the set up for aligning the ball to the PSM on a rotary table, the table was not used in the alignment, it was simply a convenient place to do the alignment.

Fig. 4 Means of holding a ball on the CGH while aligning its center to the PSM

**4.3 Secure mounting of the balls**

In the original implementation of adding datum balls to CGH's they were cemented directly to the CGH. The actual mechanical connection of a steel ball to a glass plate with an adhesive such as epoxy is problematic in two respects; the joint with the ball standing proud of the plate is highly susceptible to a lateral blow, and if the blow is sufficient to knock the ball loose there is a high likelihood of the cement pulling out a piece of the glass due to the nature of the bond.

Further, a bond at the base of a ball to a plane surface is not a mechanically strong bond because of the small lateral extent of the bond. We feel a better means of fastening the balls to the CGH is via the nests used for the SMR's used in conjunction with laser trackers. The Fresnel zone pattern is adjusted in radius to compensate for the thickness of the nest and the ball/nest pair is used to locate the nest which is then cemented around it periphery. The lower profile of the nest makes it less vulnerable to getting a sideward blow and the greater area of the cemented joint makes it less likely the nest will be knocked off the CGH. Of course, in the worst in instance of the nest bond being broken the damage to the CGH would probably be greater.

Fig. 5a and b show a commercial[5] ½" diameter SMR ball nest, and a ½" ball mounted in the nest. The commercial nest only comes in a 1/2" version as the smallest size so there is a limit to using this method of mounting balls. A small magnet is located in the nest to hold the ball even if the CGH is used upside down..

Fig 5a  A ½" commercial SMR ball nest

Fig 5b   A ½" ball mounted in the nest

## 5. CGH BASED FIXTURE FOR THE CEMENTING OF A DOUBLET LENS

### 5.1 CGH fixture design for cementing the doublet

Now that we have explained how balls may be precisely aligned and affixed to a CGH using a ASM or interferometer, we will proceed to demonstrate the design of a fixture for cementing a doublet lens that requires no rotary table or precision vertical stage. Once the ASM is initially aligned to the CGH fixture there is no need to move the ASM during the remainder of the cementing process.

The particular lens we used to demonstrate the process was an Edmund P/N 32-927 whose properties from Zemax are shown in Table 1. The lens has a nominal efl of 400 mm and a 40 mm diameter. The design of the fixture started with the usual assumption that the meniscus flint would be placed convex side down on a support, in this case 3 balls, and the crown would be cemented to the flint by adding it on top. The critical dimensions of the design are shown in Fig. 6. The one dimension that everything in the fixture is tied to is the height of the center of curvature of the concave surface of the flint when supported on ¼” balls, namely 179.08 mm.

Table 1 optical properties of Edmund 32-927

| Surf | Type | Radius | Thickness | Glass | Diameter |
|---|---|---|---|---|---|
| OBJ | STANDARD | Infinity | Infinity | | 0 |
| STO | STANDARD | 257.16 | 8.5 | N-BK7 | 40 |
| 2 | STANDARD | -169.03 | 4 | N-SF5 | 40 |
| 3 | STANDARD | -473.08 | 394.5902 | | 40 |
| IMA | STANDARD | Infinity | | | |

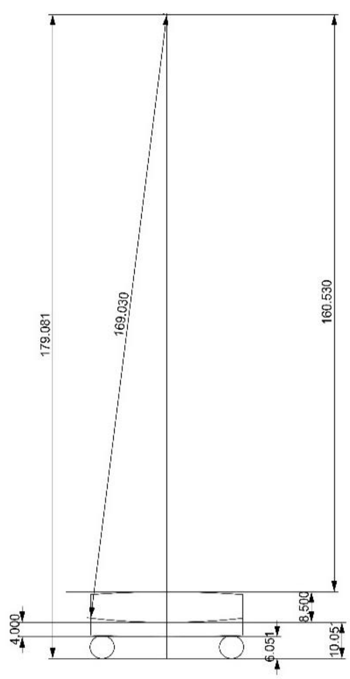


Fig. 6 Critical dimensions of CGH fixture for cementing an Edmund 92-327 doublet

When an ASM is focused at 179.09 mm above the CGH and centered on the Fresnel pattern under meniscus, the ASM will also be focused on the center of curvature of the concave side of the meniscus. The 3 balls supporting the meniscus are centered around the Fresnel pattern. This guarantees the center of curvature of the convex side of the meniscus lies on the axis of the Fresnel pattern. The meniscus is then slid on the 3 balls until the center of curvature of the concave side is centered on the ASM crosshairs. This assures the meniscus is centered on the fixture, that is, its optical axis lies on the axis of the Fresnel pattern.

When the crown is added to the flint we would like the light through the assembled lens to also focus 179.09 mm above the CGH so we do not have to move the ASM. This is done by adding a second modified Fresnel pattern concentric to the first with an aspheric design to send the light back through the lens to focus stigmatically at 179.09 mm. Fig. 7 shows how the CGH was designed for these functions.

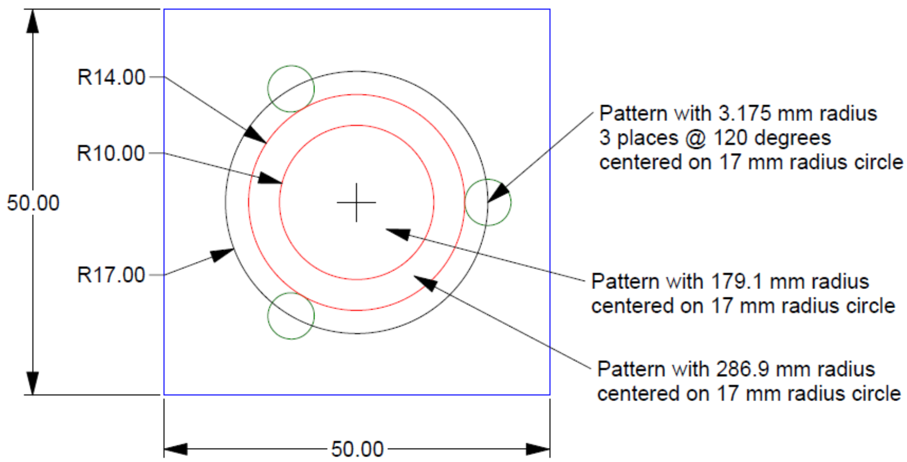

Fig. 7 Layout of the CGH for cementing of the Edmund 92-327 doublet

Fresnel patterns for 3 – ¼" diameter balls were located on a circle with a 17 mm radius to support the convex side of the meniscus, and centered on the main Fresnel pattern. The inner main Fresnel pattern was designed to focus 179.1 mm above the CGH substrate, and served two purposes. Before the meniscus is placed on the fixture, the ASM is aligned to the spot reflected from this pattern and fixed in place.

Once the meniscus is placed on the fixture the 3 balls mechanically locate the center of curvature of the convex side on the axis of the main pattern. Simultaneously, the center of curvature of the concave side is located close to the point 179.1 mm above the CGH so that a slight sliding of the meniscus on the balls will center the reflection from concave side on the ASM crosshairs as well.

The outer aspheric Fresnel pattern is designed to focus 286.9 mm above the CGH substrate. This is just the right conjugate so that light focused 179.01 mm above the CGH will re-focus at 179.01 mm for the cemented assembly. This allows for the centering of the crown to complete the assembly without ever having to move the ASM or interferometer. This CGH fixture during the process of cementing the third ball is the one shown in Fig. 4.

### 5.2 Using the CGH fixture to cement the doublet

It is almost impossible to purchase the halves of a commercially available doublet, so the first thing to do is de-cement the doublet. This is easy and difficult depending on the resources available. Warming gently to 550°F in a conventional kitchen oven did the trick, the lens simply fell apart. The lens was brought back to room temperature overnight. The difficult part was removing the remaining cement from the two surfaces. Relatively safe organic solvents would not touch the cement.

Luckily there was some thin cloth saturated with a fine abrasive available (although the source is unknown to me) and by using one surface as a matching tool to the other surface, the cement was rather quickly removed from both mating surfaces with no damage to the glass.

Once the two halves were available the cementing process proceeded as planned. A PSM was located above the CGH fixture and focused and centered on the spot from the 179.1 mm Fresnel zone. The meniscus was inserted and tapped into place so that the reflection from the concave side was centered on the same spot 197.1 mm about the fixture. Since this was not a production fixture and it was essential that the meniscus did not move during the cementing step, the meniscus was secured to the 3 balls with little dabs of hot glue.

The crown was then "cemented" to the flint using light oil since we didn't really want to cement the two components together; this was an experiment. The oil served as a satisfactory cement for the purposes of alignment of the second half, and light from the outer zone of the CGH focused as expected and was used to center the crown. Fig. 8 shows the reflected spots from the CGH during the alignment of the PSM to the CGH, the concave surface of the flint and the assembled doublet.

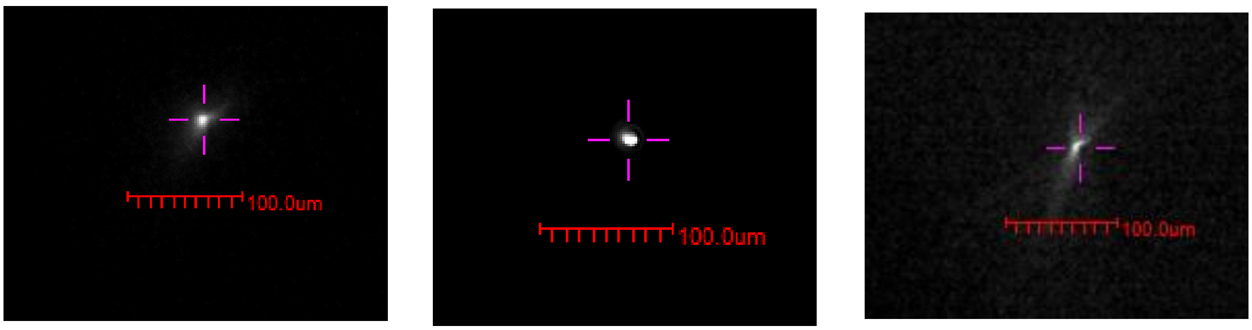


Fig. 8 Reflected spot from the CGH prior to inserting the meniscus (left), spot from the concave side of the meniscus (middle), and spot from the assembled doublet (right)

Fig. 9 shows the meniscus half of the lens supported on the 3 balls and centered on the CGH, as well as a picture of the "cemented" doublet on the fixture.

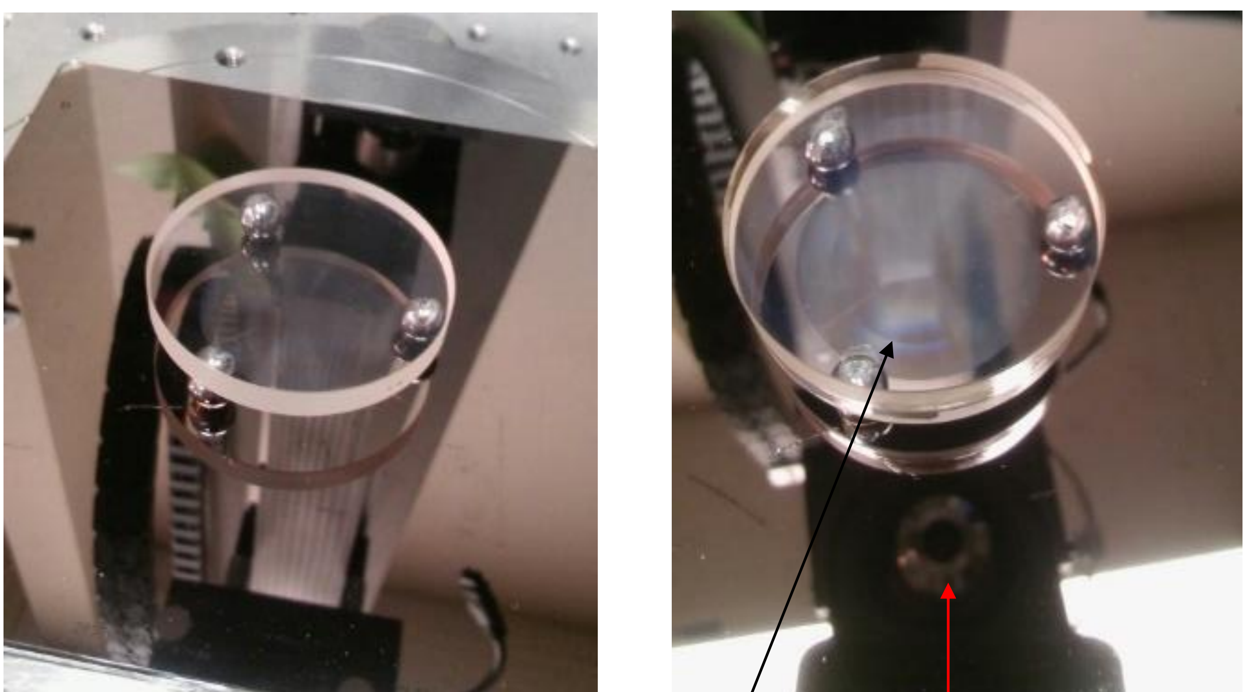

Fig. 9 Meniscus half of doublet centered on CGH and 3 ball support (left) and "cemented" doublet (right)

Boundary between the two CGH patterns PSM objective

The photographs in Fig. 9 are a little confusing because the vertical stage holding the PSM and the PSM objective are reflected in the chrome background of the CGH. In the right-hand picture, the two zones of the CGH are just visible, as is the objective of the PSM just below the doublet.

As is clear from Fig. 8 the reflected spots are centered in the PSM to a couple µm, and from the read out of the centroid on the PSM to ±1 µm. Since the distance to the CGH is about 180 mm, this means that the centration of the two halves is good to a couple µm, or about 1 second of arc. This was done with a rather simple set up and without moving the PSM once it was centered on the CGH.

**5.3 Practical CGH fixture for cementing a doublet**

The example above demonstrates the feasibility of making and using a CGH fixture for cementing a doublet, but it is not a practical fixture in that there is no good way of holding the meniscus in place while cementing the crown half of the doublet. In the example, a bit of hot glue was used to hold the meniscus in place while centering the crown.

What is needed for a practical fixture is to use vacuum to hold the meniscus in place once it is centered, and this requires a ring type support that is not perfectly kinematic, but a good practical choice, particularly if the ring, or tube, is made of a hard ceramic so that the critical seat will not wear and is not prone to damage as a metal ring might be.

Using a ring adds complexity to centering the ring on the CGH. One way to center the ring precisely is to use a dummy meniscus that has the same radius as the convex side of the real lens to be cemented with the concave side concentric to the convex side. The dummy lens can first be used to lap the seat on the ring or tube support, and then used for centering the ring with respect to a third Fresnel pattern designed to focus at the radius of the convex side plus the height of the ring. This permits the ring seat to be centered with the same precision as the 3 balls. The balance of the CGH design would be the same as the preceding example. In this case, the ASM would have to be moved between centering the ring and using the fixture for cementing, but once the ring seat is cemented to the CGH there is never any need to use this conjugate again. It is a one-time conjugate used for constructing the fixture. Fig. 10 shows a schematic representation of such a practical CGH cementing fixture.

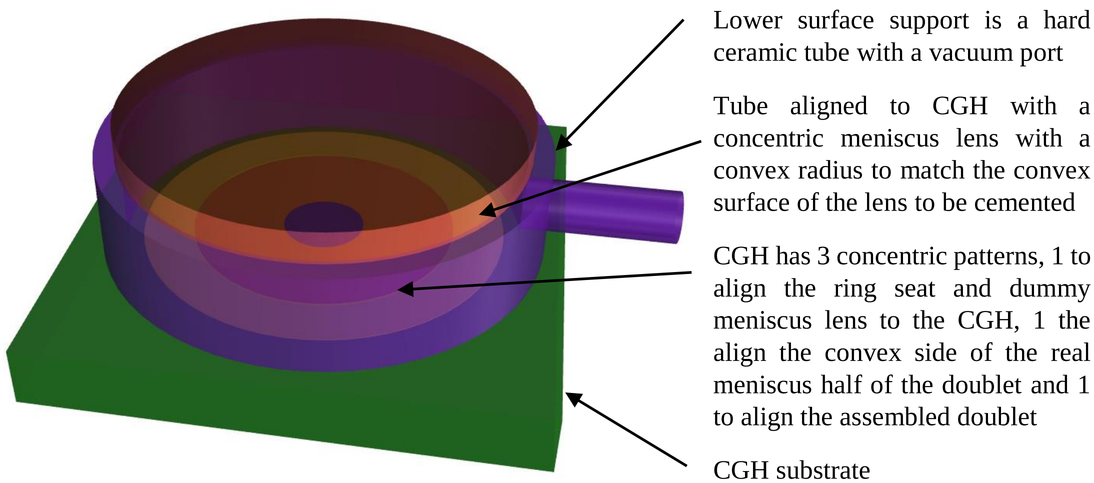


Fig. 10 A practical CGH fixture for cementing doublets

While the practical fixture is shown for cementing a doublet, it is obvious that a more complex CGH fixture could be designed for cementing 3 or more elements. The ring patterns on the CGH do not have to be particularly wide to produce an easily visible point on which to focus the ASM, and it seems most efficient to match the diameters of the rings with the radii of the patterns to keep the f/# cones approximately the same. Other than that the rings do not have to be in any particular order from center to edge.

## 6. GENERAL FIXTURE FOR TESTING SINGLET LENS ELEMENTS IN TRANSMISSION

### 6.1 Case for a singlet with spherical surfaces

With the background of cementing the doublet, it is easy to understand a more general fixture for testing singlet lenses in transmission, the way the lens will be used in practice, while also checking for centration. By adding 2 additional balls to the CGH that define the optical axis of the lens using the periphery of the lens, the entire functional performance of the lens can be measured in one step. For conventional lenses with spherical surfaces this is generally not necessary as process controls largely guarantee a functional lens, but with the increasing use of molded, aspheric optics, many lenses must be tested for functional performance by rather costly methods. A CGH fixture would be a method to provide full functional testing at a fraction of the cost of more conventional methods.

To understand the method, look at a biconvex singlet supported on 3 balls just as in the case of the doublet as shown in the schematic Fig.11. The 3 balls are arranged symmetrically about 2 concentric CGH zone patterns, one a Fresnel zone pattern to define the location of the ASM or interferometer, and the other a pattern designed to produce a perfect wavefront when viewing the perfect, centered singlet in double pass transmission at the same height as the first image.

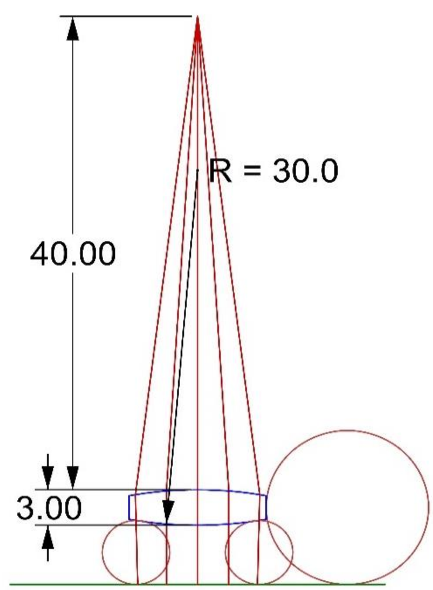


Fig. 11 Schematic representation of a biconvex lens supported on 3 balls with its periphery defined by another 2 larger balls

The BK7 lens has a nominal diameter of 11 mm, and assume for the moment that the balls defining the location of the lens edge are exactly at 5.5 mm from the center of the CGH test pattern. If the lens has been manufactured perfectly to all dimensions on the drawing, the ASM or interferometer will see a centered image with no wavefront error.

If, however, there is a one minute wedge in the otherwise perfect lens there will be an image shift of 28 μm and the image shape will show coma of about ¼ wave, easily discernable with a PSM. That the error is a wedge error is easily determined by rotating the lens 180° on the balls and observing the image shift is equal and in the opposite direction.

We assumed the lens was a nominal 11 mm diameter but it must fit in a nominally 11 mm diameter bore so a typical tolerance on the diameter might be 10.99 +0, - .01 mm, while of course the bore would be slightly oversize. If we now assume the balls defining the periphery of the lens are still at exactly a 5.5 mm radius, but the lens has been edged to the low side of the tolerance and is in fact 10.99 mm in diameter, then the lens will be decentered by about 5 μm, but really tilted about the center of curvature of the lower side by an angle of 0.005/30 = 35 seconds of arc. This produces an image shift of 13 μm and clear coma with an OPD of about 0.3 waves at 0.64 μm. In this case, if there is no wedge, when the lens is rotated 180°, there will not be a reversal of the image position so the two likely causes of image displacement can be separated.

Since both of the centering errors considered are about the same magnitude, a reasonable test for this set up might be that as long as the image were not too mis-shapen and the image was within, say 25 μm of the crosshairs in the ASM independent of how it was rotated on the 3 balls, the lens would be considered in spec. Such a check would take only a matter of a few seconds using a PSM, and probably no longer using an interferometer.

**6.2 A practical version of the lens checking CGH fixture**

Fig. 11 shows the design of the fixture strictly following the ideas of using balls as kinematic references. This is a rather unwieldy approach to the fixture that could be made more practical by mounting the ball that define the edge of the lens in tubes that are slightly smaller in diameter than the balls. Since the edge of the lens is defined as the "B", or secondary datam in most cases, the balls only need to be precisely located in the plane parallel to the CGH and so a slight variation in height between these two balls will not affect the precision of the fixture. Again, the ball Fresnel patterns need to focus about midway up the periphery of the lens to precisely locate the balls defining the edge. Fig. 12 gives an idea of this sort of fixture.

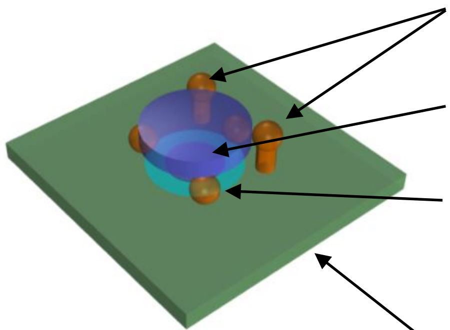


Fig. 12 An example of a practical CGH fixture for checking the figure and centering of a lens in transmission

One could think of the fixture in Fig. 12 in much the same way as a test plate as used in traditional lens manufacture where the test plate was used to qualify a surface of a lens to see that it met specification for figure and radius. The CGH fixture has the same function but now for the whole lens. Where two test plates were needed traditionally, one for each surface, now one CGH fixture qualifies the lens in a fully functional way, that is, in transmission as it will be used in practice, for overall power, figure and centering. By checking the lens in this way, there is no uncertainty in the quality of the glass in terms of inhomogeneity and striae, the tolerances on the two radii can be looser as long as the lens has the correct power as demonstrated by the test and a separate test for checking centering is unnecessary.

Now, just as two test plates were associated with a particular lens, one CGH fixture could be associated with a particular lens, and be a far more complete indication of the likelihood the lens will function in the final product as specified in the design. Finally, in terms of cost, such a CGH fixture would be comparable in price to a pair test plates.

**6.3 A similar fixture but for a double asphere**

For this example we use a meniscus lens with aspheres on both surfaces. The specification calls the convex surface with a radius of 32 mm the primary, or A, datum so this surface is set on the 3 balls on top of the CGH as shown in the Zemax drawing in Fig. 13. This is the same basic set up as in Fig. 11 with the exception that the CGH pattern to the right is more complex than for the biconvex lens. The focus of the CGH null test is 110 mm from the lens.

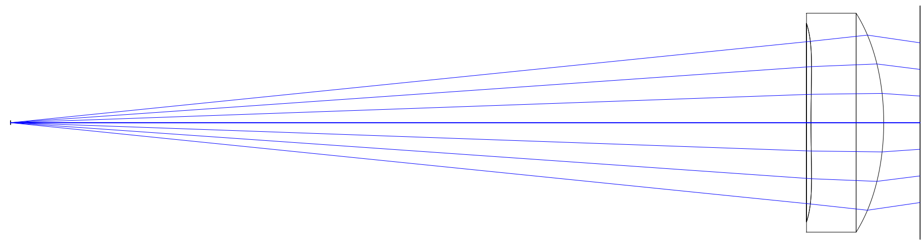

Fig. 13 Meniscus lens with aspheres on both sides supported on 3 balls (not shown) on a CGH at the right

Because the convex surface is supported on 3 balls centered about the CGH pattern, the center of curvature of this surface will always lie on the axis of the CGH, at least for the small tilts and decenters we are talking about. The asphericity of the surface is too small to move the center of curvature off the axis of the CGH as long as the tilts are small. In general this assumption will be true for all lenses but should be checked for each new design.

Assume, as in the case of the biconvex element, there are 2 more balls that define the periphery of the lens to the nominal diameter. There are now 3 remaining unconstrained degrees of freedom to look at; the whole, perfect, lens can be tilted about the center of curvature of the convex side on the 3 balls if the diameter of the lens is not the precise nominal diameter, there is a wedge between the two aspheric surfaces so their optical axes will not be parallel, or the concave surface can be decentered with respect to the convex so the optical axes are parallel but not coincident. Each of these misalignments has a different signature allowing the types of error to be separated in this case.

A Zemax analysis of this generic, but typical molded lens shows that if the whole lens is tilted because it is edged to give clearance to the bore by 5 µm, the lens will tilt about half a minute of arc when pushed against the balls defining the periphery. The image will be displaced by 28 µm and becomes distinctly comatic (about 2 λ PV). As the otherwise perfect lens is rotated against the balls defining the periphery the image maintains its displacement.

If there is an equivalent half minute of wedge between the surfaces, or an edge thickness difference of 4.4 µm, the image moves 32 µm but the image shape or symmetry is affected very little. In this situation, as the lens in rotated the image displacement will follow the rotation.

If the concave surface is decentered with respect to the convex by 5 µm the image only moves 4 µm but there are 4 waves of coma. Again, the coma will rotate with the lens as it is rotated. It is clear that the 3 types of centering error can be easily separated in this case although it is difficult to make the case that this will be true for all designs. However, this example makes it clear, a very simple fixture can be used to quickly inspect rather complex lenses for performance in the way the lens will be used in practice, that is, in transmission. Further, not only can centration errors be spotted, but index variation and wavefront errors as well. This is particularly important for molded aspheric lenses.

## 7. CONCLUSIONS

We have shown that it is easy to locate balls, and using the same principles, polished cylinders, to computer generated holograms to precisions of ±1 µm and cement them in place to make a fixture. These mechanical features are then permanently located to the CGH substrate and serve as datums for aligning other optical and mechanical elements. The designs have built-in optical alignment features so that they may be re-assembled if they are damaged. Further, because fixture is based on a low expansion photomask substrate, it will be dimensionally stable unless it is dropped, in which case it will probably be in pieces rather than warped in a not obvious way as is often the case with metal fixtures. However, a new CGH can be easily and precisely reproduced from the design of the original.

The fixtures designed and used as suggested here can be used without expensive auxiliary mechanical equipment such as air earing rotary tables and precision vertical stages. Yet these simple fixtures can be used to test individual optical elements as they will be used in final assemblies for transmitted wavefront, power and centering in one simple test that would take a matter of seconds. It is suggested that an autostigmatic microscope be used because they are sensitive to wavefront errors as small as 80 nm P-V, but these same fixtures can also be used with interferometers should greater wavefront sensitivity be desired.

The fixtures for inspecting individual lens elements, be they elements with spherical or aspheric surfaces, can be thought of as a "test plate" used traditionally for inspecting surfaces for power and irregularity, but now a single CGH fixture checks the entire lens for transmitted wavefront quality and centering. This fixture would be intimately associated with the particular lens just as a pair of test plates were associated with a particular lens in the past.

It is also clear that while some fairly simple CGH test fixtures have been described here, it is obvious how more complex but similar fixtures could be designed and made. Finally, we have shown not only how to make the fixtures in theory but have demonstrated the working of one and suggested practical means of implementing others.

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