Determination of the unique optical axis of assembled lens systems

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ABSTRACT

Measuring the quality of alignment of an assembled compound lens is often necessary. This raises the question of what axis to use as a reference axis for this measurement. We suggest that the reference axis should be the optical axis of the assembled system and that this axis is unique for each assembly.
Keywords: Optical alignment, optical axis, Point Source Microscope, lens centering, Bessel beam, tabletop alignment

1. INTRODUCTION

We intended to focus on finding the optical axis of imaging optics assembled in a cell so the axis could be used as a reference axis against which the misalignment of centers of curvature could be related. A more pressing need is the alignment of modules of optical components for guiding light from a source to a location where the light interacts with another object for material processing or atomic cooling. Along its path from source to the point of interaction, the light is often "prepared" with passive and active optical components to interact more efficiently with glass for scribing or atoms for cooling. This is a different kind of alignment from stacking lenses in a cell for imaging purposes. This alignment is all on an axis, simply getting light to go straight through a system with minimal distortion. For this reason, the paper will focus on the 3D tabletop alignment of optical components, but the topic still relates to aligning the optical axes of individual components, as would be the case for lenses in a cell.

We use a Bessel beam as the reference axis for alignment because it propagates through optics as an ABCD ray [1,2]. Since this is the main supposition of this paper, we show that the beam propagates as ABCD matrix optics [3,4] indicates and matches the theoretical results of physical optics propagation analysis. Furthermore, a Bessel beam's unique qualities, such as its no-diffracting nature and the small size of its central peak, make it well-suited as a reference axis. Coupled with the ABCD assumption is that all angles and distances from the reference axis are small, so the calculations are considered paraxial.

The paper is organized with a section describing a Bessel beam followed by proof that a Bessel beam propagates as an ABCD ray. Additionally, we show that the ray can be diffracted into multiple beams at specific angles so that relative ray angles are known after propagation through each component. We then show how a first lens is aligned precisely to a Bessel beam and how additional lenses are aligned to the first by following the undeviated beam.

2. WORKING DEFINITION OF A BESSEL BEAM

We need a working definition of a Bessel beam because we draw a correspondence to an optical ray traced using ABCD matrix optics. When looking at the Bessel beam intensity pattern in a plane perpendicular to its propagation, we see not a ray but a locus of points formed by the constructive interference of wavefronts symmetric about the Bessel beam's propagation direction.

Because this locus of constructive interference propagates like an ABCD ray, it is a useful concept to think of the Bessel beam as a ray that geometrical optics describes, but it is not a ray in a conventional optics sense. This difference is important in understanding the propagation behavior of the Bessel beam because there are instances where you observe the Bessel beam behaving in ways that real, physical rays do not. The value of the concept of Bessel beam propagation gets lost if it is thought of as a real physical ray rather than a locus of points of constructive interference.

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An example of this is looking into a lens with an autostigmatic microscope to find the second principle plane. The microscope moves the geometrical optics distance from the lens surface to the principal plane, yet theoretically, the distance should be about 35% less because of the index of the glass. While this difference between the Bessel beam locus of points and real rays is confusing, it is also very useful. In this example, you do not have to think about the index of the glass; you are directly measuring the distance to the principal plane, the difference between the effective and back focal distances.

3. PROOF THAT A BESSEL BEAM BEHAVES AS AN ABCD RAY

In recent theoretical work [5], Zhaowei Chen showed that using Zemax physical optics ray propagation or a Fresnel propagation model in MATLAB, he got the same result. In this case, his model was that of a quasi-Gauss-Bessel beam (QGB) in the sense that the beam was generated with a zone plate of evenly spaced concentric circles illuminated with a spherical wavefront produced by a Gaussian intensity distribution at the end of a single more fiber. As opposed to a pure Gauss-Bessel beam produced with a plane wavefront and having a finite length and a constant diameter central core, the QGB is much longer than a true Gauss-Bessel beam. The central core slowly increases in diameter, as do the surrounding rings, as it propagates. These properties are well illustrated by Dong and Pu [6].

The theoretical model also agrees with the experimental result that the central core expands in diameter with propagation distance to the limits of the experiment's resolution. To further test these results, a lens was inserted in the QGB and decentered by controlled amounts, and the deviation of the QGB was measured as a function of propagation distance. Again, the experimental results matched the theory to about 1%, on the order of the calibration of these various components of the experimental setup.

3.1 Additional proof of QGB propagation as an ABCD ray

A low spatial frequency (4 lp/mm) linear grating was inserted in the QGB to see what would happen. If one assumed the Bessel beam behaved as an ABCD ray, one would expect the beam to be diffracted into +/- odd orders, which is exactly what happened. Fig. 1 shows the 0 and +/- 1st order QGB core spots 100 mm above that grating that are +/- 255 um on either side of the 0 order.

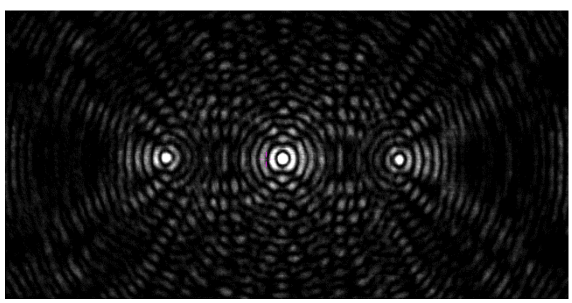


Fig. 1 Zero order QGB with 1st order diffracted beams on either side

The 4 lp/mm grating gives a diffraction angle of 2.56 micro radians at the 640 nm wavelength used for illumination. At 100 mm from the grating, the theoretical separation is 256 um while the measured spacing is 255 um. (Higher order diffracted beams were also present but were much less intense.)

3.2 Effect of adding a lens in the diffracted beams

Since this experiment worked so well, the next step was to add a lens on an x, y, and z stage to the setup, resulting in the arrangement shown in Fig. 2.

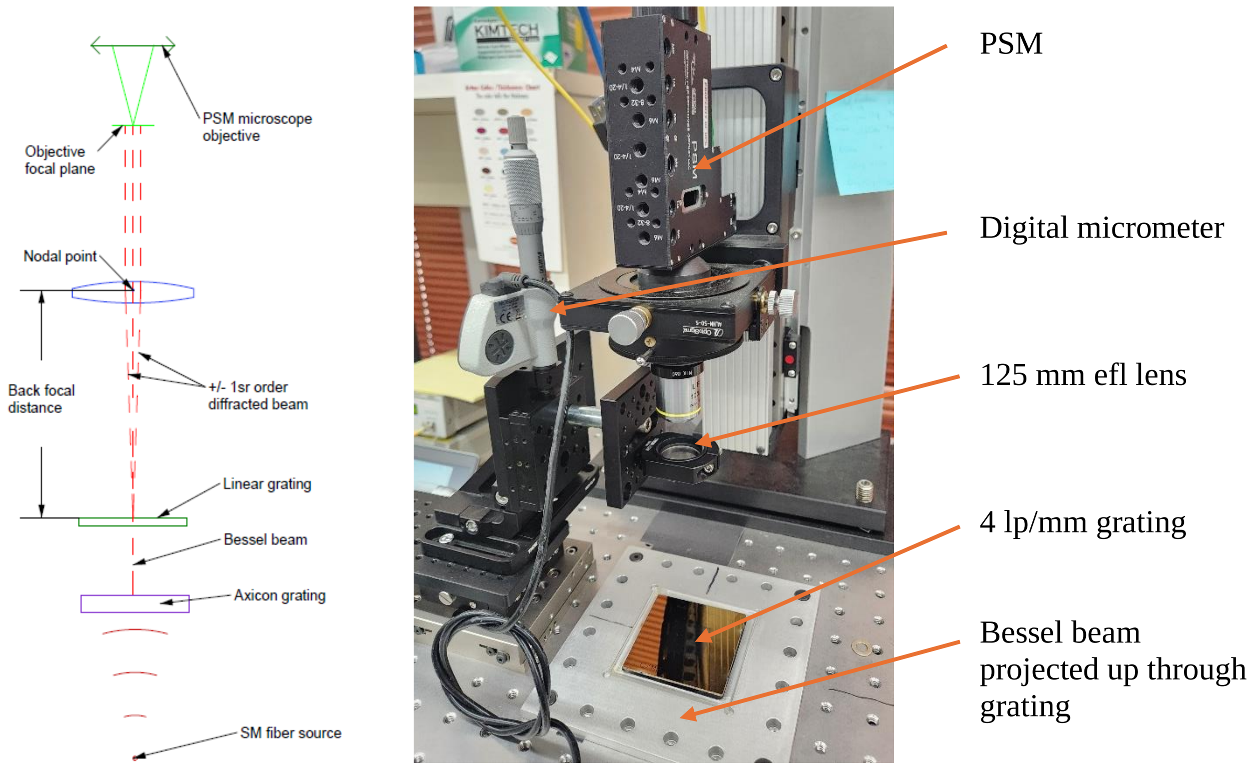


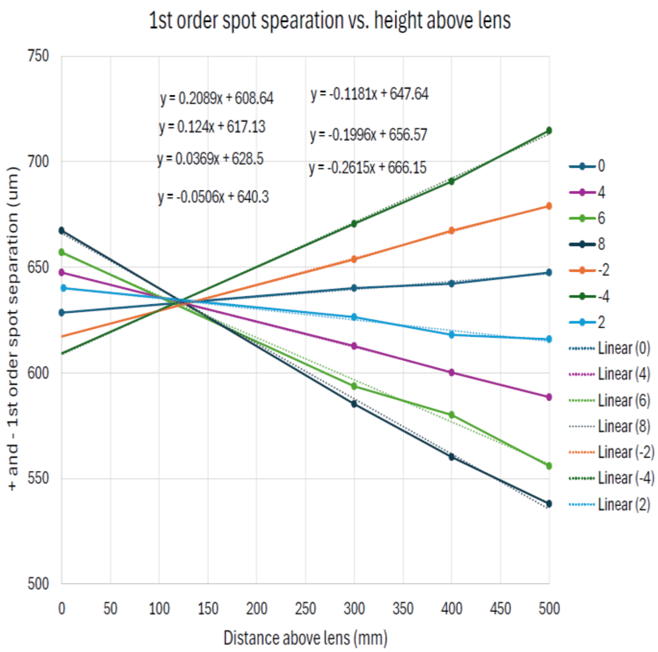
Fig. 2 A schematic diagram of the experimental setup (left), and photograph of the hardware (right)

When a 125 mm efl lens was placed about 125 mm from the grating, and a PSM autostigmatic microscope [7] was focused on the nominal principal plane of the lens, the diffracted ± 1st order beams were separated by 314.5 um when they were predicted to be separated by 320 um if the lens' principle plane were precisely 125 mm above the grating. We varied the lens height in 2 mm steps around a zero height taken as the upper surface of the lens. The measured spot separation versus lens height about the zero is shown in Fig. 3.

The lens is moved axially, and the ± 1st order ray intercepts with the lens change separation as the lens height changes. The crossing of the curves at roughly 125 mm above the lens has no significance. Rather it is the slopes of the lines of the separation of the rays versus height that is important. When these slopes are plotted versus the lens height above the grating, the zero crossing is at 1.06 mm, as seen in Fig. 4, indicating the lens was too close to the grating for the principle plane to be at exactly 125 mm. It must move 1.06 mm farther from the grating to be precisely at the principal plane.

This simple experiment shows directly that the QGB behaves like an ABCD ray. As significant as this is, it is more significant that this is a method of measuring collimation with a very low NA beam. The effective NA of the ± 1st order rays incident on the lens is 0.00256. Diffraction theory would say measuring collimation to sub-mm precision is impossible with this low an NA. It also shows that these rays give sufficient information to derive the ABCD matrix elements of all the lenses preceding where the rays were measured. [5]

Because the diffracted rays are sufficient to calculate the elements of the ABCD matrix as each new optical element is added to a chain of elements, the matrix can be checked against the ABCD matrices of the design to see if the spacings of the elements are correct in a functional manner rather than simply measuring the physical distance between elements. This improves the confidence that a system is correctly assembled step by step rather than having to wait for the testing of the entire final assembly.



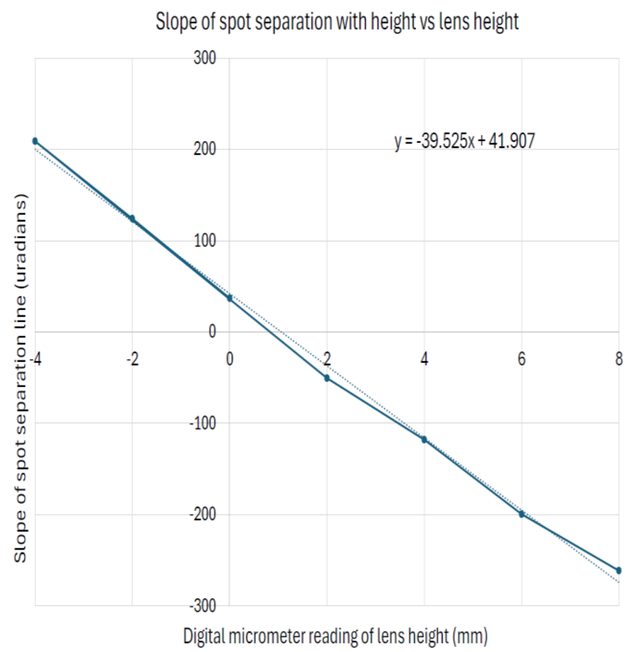


Fig. 3 Slopes of 1st order diffracted rays exiting lens

Fig. 4 Slope of exiting rays vs. distance of the lens from the linear grating with zero near the principal plane

4. USING A BESSEL BEAM TO ALIGN MULTIPLE ELEMENTS

4.1 The optical axis of a lens

The optical axis of a single element is the line between the centers of curvature of the two surfaces. This definition means that a single ray coaxial with the optical axis is normally incident at both surfaces and propagates through the lens undeviated in position or angle. For a multi-element lens, we can still use this concept of no or minimum deviation to define the optical axis of a lens. From a practical view, this definition has a weakness in that when a lens is rotated about an axis perpendicular to the optical axis where the intersection of the axes is within the lens, a single optical axis ray is relatively undeviated for small rotation angles. This is why we also need to access a center of curvature of some surface within a lens of one or more elements to align it with a reference axis as precisely as possible.

4.2 Precise alignment of a single element

If a single ray passes through the nodal point of a single element, the lens barely deviates the ray if it is not tilted far from its optical axis, as shown in Fig. 5. To precisely define the axis of the lens in a centering instrument such as a PSM, the PSM must simultaneously be focused at one of the centers of curvature. Besides the Bessel beam, there is no other datum to focus on, and the long optical lever arm gives good angular precision. However, a useful center of curvature is often only accessible by looking through another surface. For example, in Fig. 5, the accessible center of curvature of the first surface must be viewed through the second surface and appears as the optical center of curvature due to the power in the second surface as shown with the green lines in Fig. 5.

When a Bessel beam is used as a single gut ray, or centered ray from infinity, and is centered on the PSM before inserting a lens, we know that the ray passes through the nodal point when the lens is inserted in the beam and the ray is again centered on the PSM. To center the lens precisely, the PSM must be focused on the plane of the optical center of curvature. At this axial location, both the Bessel beam and the optical center of curvature are visible simultaneously because the PSM's light source illuminates the curvature's optical center. The lens is free of tilt and decenter when both the transmitted

Bessel beam and the reflected spot from the center of curvature lie on the crosshair of the PSM. This method uniquely defines the singlet element's optical axis, particularly when the second center of curvature is inaccessible.

Consequently, it is possible to install the first element of an optical assembly perfectly aligned because sufficient degrees of freedom exist to decenter and tilt the lens to align its optical axis to the initial Bessel beam. Then, the first element's optical axis and the co-axial Bessel beam become the reference axis for all the remaining alignments.

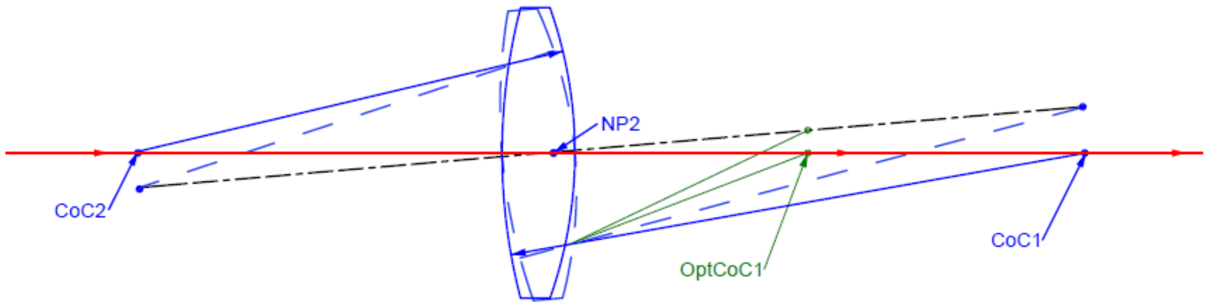


Fig. 5 Untilted and tilted lens showing the gut ray is virtually undeviated when the lens tilts about the 2nd nodal point

4.3 Adding additional lens elements

In the upper part of Fig. 6, we assume that the first lens is perfectly aligned to the reference Bessel beam using the technique described above to ensure that both the Bessel beam and the center of curvature of the first surface are centered on the PSM crosshairs. When this is the case, the PSM is moved to the back focus of the lens, and the grating producing the Bessel beam is used as an autocollimating flat mirror. This makes it possible to locate a ball at the back focus to < 1 µm in x, y, and within ±2 µm in z using a 10x objective on the PSM. If one wanted to place a spatial filter or a grating to diffract the beam at this location, this is an easy, precise method to locate the spot.

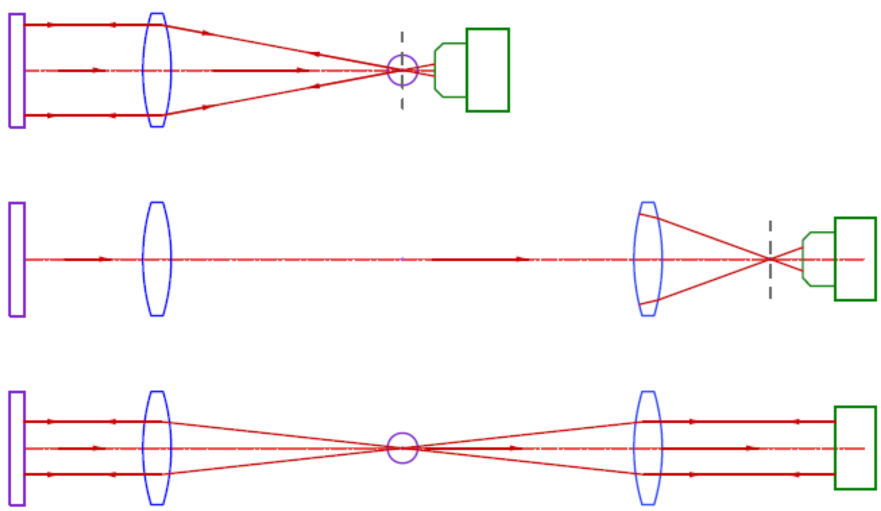


Fig. 6 Method of aligning a first element in tilt and decenter to a reference Bessel beam where the necessary degrees of freedom are available and then checking the alignment by moving the PSM to the focus of the lens (upper), adding a 2nd element using a center of curvature and the Bessel beam (middle) and checking the alignment of the pair (lower)

The second element is presumed to be perfectly aligned, and the Bessel beam propagating through it is now used as the reference axis for the next lens. It is possible to double-check the alignment by removing the objective from the PSM and replacing the ball in its holder where the two lenses focus. The PSM is aligned in angle, so the light reflected from the center of the ball is centered on the crosshair. Then, the ball is removed, so the light reflects off the plane grating. If there is perfect alignment, the light from the grating will also focus on the PSM crosshair. This dual use of the PSM as an autostigmatic microscope and autocollimator makes it possible to double-check almost all steps to 3D alignment.

4.4 Adding additional elements assuming only one degree of freedom

In 4.3, it was assumed that we could align the second element in tilt and decenter, as is the case with tabletop alignment. While, in theory, we can always align the first element to the cell perfectly, it is usually impossible to do this for the next elements mounted in a cell in all but the highest-quality lenses. Usually, the second element is constrained by the seat of the curved surface is sitting on, or the flat seat edged on the lens. Here, we limit the discussion to the convex surface being constrained by the seat and assume the seat is slightly decentered relative to the Bessel beam axis propagating from the first element. Given the constraint of the decentered seat, what is our best option for centering the second element?

This is the same question as how we best align a single element where we know the center of curvature of the first surface is decentered relative to the reference Bessel beam. Since there is only one degree of freedom, we need only measure the transmitted beam in one location because measuring in additional locations gives useless information. The best location is as far from the lens as is practical to minimize the tilt necessary to correct the decenter. Figure 7 shows the concept.

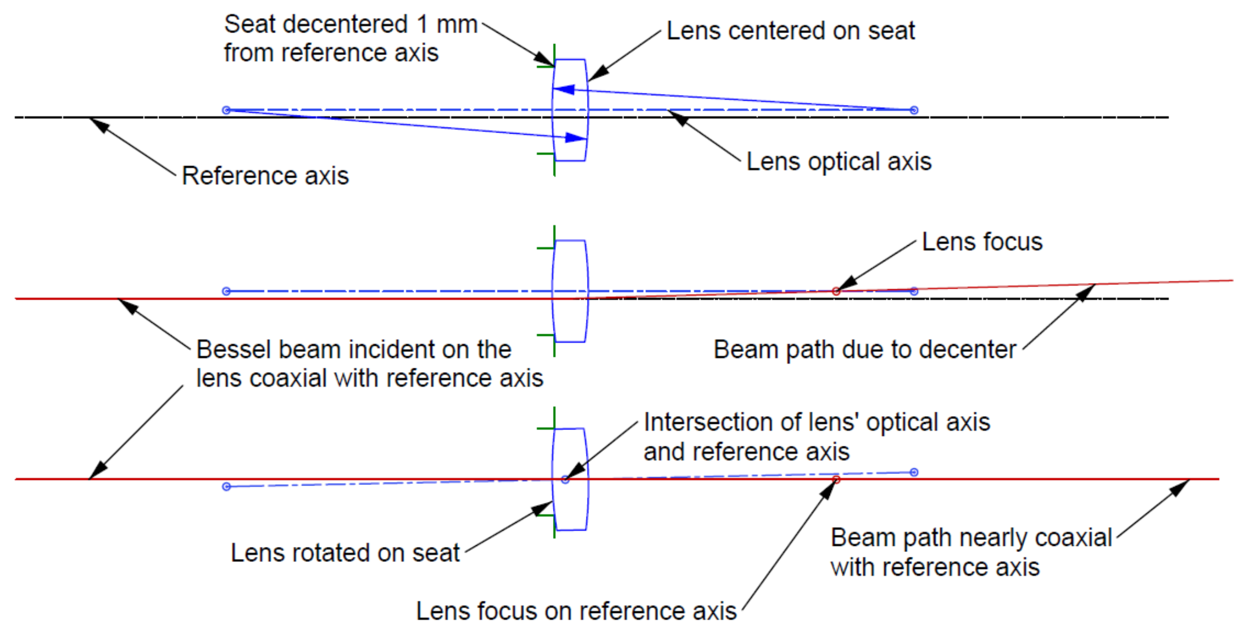


Fig. 7 shows a Lens on a seat decentered relative to a reference axis (upper), the deviation of a Bessel beam coaxial with the reference axis by the decentered lens (middle), and the deviation optimally removed by rotating the lens in its seat to make the optical axis intersect the reference axis somewhere inside the lens axially.

Even though the 1 mm decenter of the seat in Fig. 7 is large and done so to make the example clear, the transmitted ray does not deviate by more than 41 µm by the time it reaches the second lens surface. Also, the beam's angular deviation is just 35 arc seconds for the 1.189° tilt required to bring the beam back to the reference axis measured 200 mm beyond the lens focus. In a real lens assembly, the decenter would be a maximum of perhaps 0.1 mm, so all the values here would be 10 times less than in this example and quite modest in terms of typical lens tolerances.

The important point is to minimize the gut ray deviation, the lens’s optical axis must intersect the reference axis, or Bessel beam, somewhere inside the lens axially. The exact location in the lens will depend on how far from the lens the beam deviation is measured to determine the optimization. From simulations with different powers for the lens, the angle to correct the decenter remains nearly the same for all cases until the power approaches zero, as in a meniscus with concentric surfaces.

A consequence of having the optical axis and reference axis intersect somewhere inside the lens is that the centers of curvature will not lie on the reference axis but on opposite sides of it by about the decenter of the seat. This result differs from the usual approach to getting the centers of curvature of the axis of the rotary table, which is often used in lens centering.

A further result of this alignment method is that neither center of curvature need be accessible. All that is necessary is that the initial Bessel beam is available for centering the detector. After each new surface is added, the Bessel beam is still well enough aligned to serve as the axis of the next lens added to the path. There is the caution that small errors will necessarily creep into the alignment where only one degree of freedom is available for alignment, as is the case for any alignment method.

This has not been done before because the centers of curvature were needed to locate the optical axis of a lens and they are only visible very near the actual optical center of curvature. There were no other optical datums to center on until it was realized that a Bessel beam behaves as a single ray as it propagates, and its position and slope can be determined at any distance from a lens [8].

5. CONCLUSIONS

We have outlined a method of alignment in which a Bessel beam is used as a reference axis because it propagates through an optical system like a paraxial ABCD ray. Since we assume this is how a Bessel beam propagates, we have shown additional theoretical and experimental results to support this conclusion.

Based on the ray-like behavior of Bessel beam propagation, we show how to precisely align a single element using the Bessel beam and a single center of curvature. This gives sufficient information to align a lens in both tilt and decenter. Once the first lens is aligned, the next element uses the transmitted beam as the reference axis for the next element, which is then aligned the same as the first. This same procedure is followed along the optical path as each new element is added, assuming there are sufficient degrees of freedom for complete alignment in tilt and decenter. First-order diffracted Bessel beams permit an ABCD analysis of the assembly after each element is added to ensure the assembly matches the design.

Finally, in cases where there are not sufficient degrees of freedom for complete alignment, we show how to optimize the alignment using the single degree of freedom available. This method differs from using a rotary table to locate centers of curvature on its axis. The reason for the difference is that until the idea that a Bessel beam behaves as a ray was introduced, there was no other way to center a lens other than to look at centers of curvature.

6. ACKNOWLEDGEMENT

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REFERENCES

[1] M. Santarsiero, Propagation of generalized Bessel-Gauss beams through ABCD optical systems, Optics Communications, 132:1–7, 1996.
[2] E. M. El Halba et al., Propagation characteristics of Bessel-like beams through ABCD optical system, Optical and Quantum Electronics, 49(8):1–11, 2017.
[3] A. Gerrard and J. M. Burch, *Introduction to Matrix Methods in Optics*, Dover Publications, Inc., New York (1994)
[4] G. Kloos, *Matrix Methods for Optical Layout*, SPIE Press (2007)
[5] Z. Chen, R. E. Parks, B. Dhawan, S. P. Gurunarayanan and D. Kim, Precision optical alignment using Bessel beam propagation in optical systems, (to be published)
[6] M. Dong and J. Pu. On-axis irradiance distribution of axicons illuminated by a spherical wave, Optics & Laser Technology, 39:1258, 2007.
[7] https://www.opticalperspectives.com/product/point-source-microscope/
[8] R. Parks and D. Kim. Physical ray tracing with Bessel beams. In Proc. of ASPE Spring Topical Meeting, Tucson, AZ, 2023.