Optical Alignment using Bessel-Gauss Beams

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Abstract: The article demonstrates a new approach for achieving high-accuracy alignment with a Bessel-Gauss Beam by utilizing its property of propagating as a paraxial ray. © 2024 OSJ

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1. Introduction

Almost 30 years ago, a theoretical paper showed that Bessel-Gauss (B-G) beams propagate through ABCD optical systems like a paraxial ray [1]. More recently, we experimentally showed B-G beam propagation behavior that could be explained by paraxial ABCD theory [2]. Quite recently, we have initial indications from a physical ray propagation model in Zemax that this same behavior holds [3]. Given this unique behavior of B-G beams, we examine the consequences of this ray propagation behavior as it applies to the optical alignment of practical hardware and the tolerancing of alignment.

Before discussing the consequences of alignment, consider why alignment is important to optical system performance. These days, optical lens design is a mature discipline, and with interferometry and deterministic polishing methods, essentially perfect optical surfaces are produced for most applications. The only remaining attribute to improve optical system performance is the alignment of these components as they are assembled. This is particularly true of laser-based systems where the objective of the optical system is to transfer a bright, point-like source to a concentrated stigmatic image. This is why optical alignment is so critical.

If optical alignment is so critical, why hasn't there been more study and application of B-G beam propagation as a paraxial ray since its discovery almost three decades ago? We believe it is largely due to two reasons: the theory behind B-G beams uses sophisticated math that most hardware practitioners are unfamiliar with, and the idea that a single ray from a lens design model could be viewed in the lab is impossible. A possible third reason is that the hardware needed to produce and view B-G beams is not as familiar to optical assembly personnel as classical instruments used for alignment.

2. Consequences of paraxial beam propagation for optical alignment

The most important aspect of a paraxial ray is that its location perpendicular to its propagation direction is known from plus to minus infinity, with one exception, in the immediate vicinity of a system focus. This means that the beam location is known anywhere between the source and detector, but if the source and detector are removed, it is possible to insert the beam upstream of the source and beyond the detector. This long path produces an optical lever arm for use far outside the confines of the optical system and provides for sensitive angular alignment.

Another consequence of the paraxial behavior that is important for laser power transmission is that it makes possible the exact definition of the optical axis of a real assembled lens where the individual components are not perfectly aligned, and the optical axis is not necessarily aligned to some external feature such as the cell exterior. Using the G-B beam, it is possible to find a unique tilt and decenter of the lens assembly such that when the lens is inserted into the beam, the beam is undeviated in position or tilt. This is easy to see in the case of an individual element. If the optical axis of the element is aligned to a paraxial ray, there will be no deviation because the ray is normally incident to both surfaces. If you want light to get from a point source to a point at a distance, the most efficient path is along the optical axis of the optical system performing the transfer, whether it is laser welding or laser satellite communication.

Following the argument above, using the B-G beam means one can center lenses precisely without requiring a rotary table. The only way a paraxial ray will pass through a lens undeviated is that its optical axis is coaxial with the paraxial ray. If the exiting paraxial ray is sampled at two axially separated distances, the position of the ray and its angle are determined. Simple measurement at two axial locations is necessary to ensure precise centering in angle and displacement.

In analogy to the case above, another consequence is that we can align off-axis reflecting optics in five degrees of freedom. If a B-G is projected in a particular direction and a pair of detectors are aligned to measure the locations of the reflected paraxial ray, there is only one way of inserting the off-axis element such that the incident ray is centered in both detectors after reflection from the optic as shown in Fig. 1.

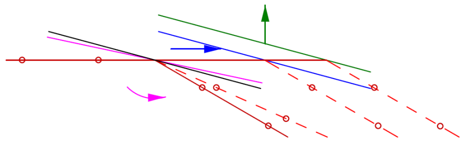

Fig. 1 Misalignment demonstration of a reflecting optic.

We use a small enough patch of the mirror to be considered plane. Then, a ray coming from the left intersects the mirror in the desired location (black line) and reflects as the solid (red) curve. If the mirror is rotated about an axis into the page, the ray deviates in angle. The circles indicate points at which the location of the beam is measured. If the mirror is translated in the direction of propagation (blue line), the reflected beam is translated. Similarly, if the mirror is translated perpendicular to the direction of propagation, the reflected beam is translated but is parallel to the correctly reflected beam.

Figure 1 shows only three degrees of freedom but if it were a perspective figure we could see the remaining two degrees of freedom, one of tilt and one of translation into the page. Since the B-G is long when produced with a spherical wavefront and that it is simple to measure the position of its central core to < 1 μm, it is easy to see that alignment to one arc second is quite reasonable.

3. Simulation of Bessel-Gauss Beam

To further investigate in the application of B-G beam in optical alignment, it is necessary to collect a substantial amount of data from various optical elements and the most efficient method is to establish a reliable simulation model.

There are many methods to generate B-G beams [4,5]. In our set up as shown in Fig. 2, we used a circular grating which is equivalent to an axicon and placed it in front of an optical fiber, which acts as a point source with a wavelength of 640 nm [2]. We measured the intensity of B-G beam at various distances after it passed through the grating. These data were used to validate the accuracy of our Zemax simulations. A MATLAB model based on physical wave propagation and a Fourier transform method were developed for crosschecking our model.

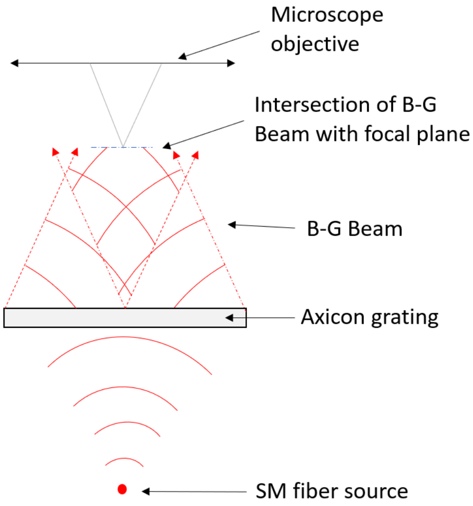

Fig.2. Schematic of the experimental setup.

The comparison among all methods is shown in Fig. 3. The simulations agree well with the reference in the region of interest, the cross-section of the central peak of the zero-order B-G beam. It is important to acknowledge that certain assumptions, such as a perfect point source and a perfect axicon, are applied in the simulations, which may introduce perceptible errors into our model, but these errors are small under the propagation distance of 600 mm.

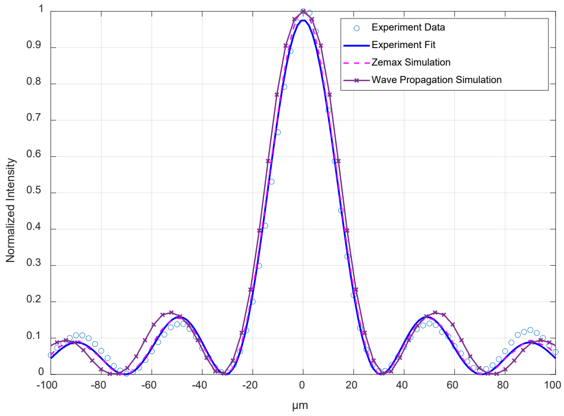

Fig.3. Comparison between the experimental data with both Zemax and MATLAB simulation. The intensity was recorded at a distance of 381.4 mm from the rear side of the grating.

With a reliable model in place, our main interest now lies in tracing the B-G beam through complex optical systems using Zemax. Our preliminary data indicate that the paraxial ABCD theory is valid in an optical system with low optical power. We are collecting more data to investigate the applicability of this theory in other cases.

4. Conclusions

Because B-G beams propagate through optical systems like paraxial rays, they offer many advantages when used for optical alignment purposes. This paper examines some of the consequences of this behavior as applied to practical examples of optical alignment. In addition, a reliable Zemax model based on physical optics function has been developed for further investigation of the applicability of the B-G beams for optical alignment.

5. References

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