Correcting an astigmatic, non-gaussian beam

K.S. Repasky, J.K. Brasseur, J.G. Wessel, and J.L. Carlsten
Physics Department
Montana State University
Bozeman, MT 59717

Abstract

An off-axis spherical mirror is used to correct an astigmatic, non-gaussian beam from a pulsed, frequency doubled Nd:YAG laser. The beam is then spatially filtered by a series of two pinholes to make the beam near gaussian.

Introduction

The output of a laser is generally not a gaussian beam. Examples of non ideal beam features include astigmatism and diffraction effects such as Fresnel patterns. Such non-gaussian beam characteristics can be caused by many effects in the laser medium and optics such as heating and turbulence in the index matching fluid in a pockels cell used for Q switching[1]. Non uniform heating in the laser rods can also lead to a thermal lensing effect which can produce a significant astigmatism in the output laser beam[2,3]. In addition to an astigmatism, the laser beam may contain high frequency, spatial structure due to clipping of the beam on various apertures in the laser.

An astigmatic, non-gaussian beam output from a laser can prove to be a difficulty in many experiments. One problem caused by an astigmatic beam is defining where the beam actually focuses. Problems also arise when making accurate comparisons with a theory based on gaussian beam propagation.

There are several ways to correct an astigmatic laser beam; the method used depends on the application. The output of a laser diode is highly astigmatic and requires a significant correction. Cylindrical lenses[4-6], and anamorphic prisms [7] are often used in correcting the output of these lasers. Laser diodes are used in various applications that require a compact package; in this case holographic optical elements (HOE's)[8,9] or an anamorphic gradient-index (GRIN) [10] lens can be used. In contrast, the astigmatism for a Nd:YAG laser can often be only slightly astigmatic. None the less, for an accurate comparison with theory, even a slight astigmatism often needs to be corrected. In this paper a Nd:YAG laser will be corrected for an astigmatism. As mentioned above, an astigmatism can be caused by thermal lensing due to non uniform heating in the laser rod.

Since the astigmatism produced is not as large as the astigmatism seen in laser diodes, other correction methods can be considered. A flexible bimorph mirror [2] or a off-axis spherical mirror [11] can be used to correct the laser beam. Due to the ease of implementation, the off-axis spherical mirror will be used to correct the astigmatism for the laser system in this paper.

This paper is organized as follows. Section II contains some definitions and remarks about beam propagation, astigmatism, and spatial filtering. Section III describes the experimental set up used to correct the astigmatic non gaussian beam. Section IV is a summary of the results of the experiment. Section V contains some brief concluding remarks.

Theory

The intensity profile of a laser beam traveling through free space can be modeled as a superposition of modes from the Gauss-Laguerre basis with the lowest order mode having a gaussian beam profile. If only the lowest order Gauss-Laguerre mode describes the laser beam then the laser beam is said to follow gaussian beam propagation. The theory of gaussian beam propagation is described in numerous books on optics [12,13] and here only a few of the properties of gaussian beam propagation are mentioned which will be useful in understanding the results of the next section.

The gaussian beam intensity profile, I(r,z), is given by

$$I(r,z)=\frac{I_0}{\left[1+\left(\frac{z}{z_0}\right)^2\right]}\times\exp\left[-\frac{2r^2}{\omega^2}\right] \qquad (1)$$

where I_0 is the peak intensity at focus, r is the transverse distance from the beam axis, z is the longitudinal distance from the focus, ω is the beam waist at z, and z_o is defined as the Rayleigh range and is given by $z_o=\pi\,\omega_o^2/\lambda$, λ is the wavelength of the laser and ω_0 is the waist of the beam at focus. Thus the waist, ω, of a gaussian beam is the $1/e^2$ radius of the intensity profile. As the gaussian beam propagates though space the beam waist varies according to the equation.

$$\omega^2=\omega_o^2\left(1+\left(\frac{z}{z_o}\right)^2\right) \qquad (2)$$

If the laser beam is a gaussian beam then it should follow the above equations. However, we have found that while our laser beam may have a profile as in Eq.(1) that looks very gaussian, as the beam propagates, we find that the beam often will not follow Eq.(2). Thus in our experiments, we generally use Eq.(2) to be the primary test to determine if we have a gaussian beam. The data that we present will be fitted to Eq.(2).

An astigmatic laser beam [14] occurs when the horizontal and vertical components of the beam focus at different locations. As mentioned above, this can be corrected by reflecting the beam off an off-axis spherical mirror[11]. For beams at normal incidence the horizontal and vertical focal lengths of the spherical mirror are identical. However, as the spherical mirror is rotated about a vertical axis such that the beam hits the mirror off-axis, the horizontal focal length decreases while the vertical focal length increases. In order to correct an astigmatism, the placement of the spherical mirror must meet the following criteria. The beam must be circular at the point where the mirror is placed; this is necessary to match the Rayleigh ranges and the positions of the foci for the vertical and horizontal components of the beam. Second, if one wants the reflected beam to stay at the same height, the beam must be more divergent in the vertical direction, because the vertical component of the laser beam has a shorter focal length when the beam reflects off a spherical mirror that has been rotated about a vertical axis. The mirror angle is then adjusted until the laser beam focuses at a single spot and is no longer astigmatic.

Often a laser beam will not only have an astigmatism, but will also have high frequency, spatial structure due to clipping by various apertures in the laser. The use of a pinhole to spatially filter out optical noise is a well known technique to eliminate this high frequency, spatial noise in a laser beam. [15-17] The size of the pinhole relative to the waist of the beam is critical for the pinhole to optimally eliminate this spatial noise. If the pinhole size is too large compared to the waist of the beam then the pinhole will not effectively eliminate the spatial noise. If the size of the pinhole is too small compared to the size of the beam waist, additional interference effects can be introduced into the laser beam. This interference can be seen as Fresnel patterns [18] as the beam propagates through space. Often these Fresnel interference patterns will develop far down stream of the spatial filter. Therefore, the proper pinhole selection is crucial to eliminate optical noise without introducing interference effects.

Experiment

The apparatus used to correct the astigmatic, non-gaussian beam is shown in Fig(1). The output of the frequency doubled Nd:YAG laser at 532nm is sent though a 100cm lens, L1, to produce a point in the beam that satisfies the criteria previously established for placement of the off-axis spherical mirror (SM); the ratio of the horizontal to vertical components of the beam waist at SM is 0.95 with an average waist of 2340μm. This point is located 50cm after L1, and an off-axis, 1m radius of curvature spherical mirror , SM, is placed there. After reflecting from the off-axis spherical mirror, the beam travels 54cm to a lens, L2, which has a 25cm focal length and collimates the beam with a waist of 2390μm. The laser beam passes though an attenuator and then is focused by L3 through a tungsten wire die that serves as a pinhole labeled PH1 in Fig(1). The focal length of the lens labeled L3 in Fig(1) is 100cm and the tungsten wire die which is placed 96cm behind the lens L3 has an aperture with a radius of 230μm. The beam waist at PH1 was measured to be 130μm. After pinhole PH1 the beam is focused again through a second pinhole labeled PH2 in fig(1). The lens labeled L4 in Fig(1) is placed 86cm behind PH1, and has a focal length of 35cm. The lens L4 focuses the beam to a spot size of 72μm. A second tungsten wire die with an aperture with a radius of 127μm is used for PH2. The beam quality after the second pinhole was inspected by placing a 35cm lens 80cm behind PH2 and measuring the beam waist as the beam went though focus.

Measurements were taken as follows. The foci of the following lenses were mapped out: after L3 with L1, L2, SM, and PH1 removed, after L3 with setup as shown in Fig(1) but with PH1 removed, after L4but with PH2 removed, and after L5. A pulnix TM-745 CCD camera was used to measure the horizontal and vertical beam waist at several locations along the beam path as the beam passes through focus. At each location 30 shots of the pulsed laser were collected and the average radius in the horizontal and vertical directions were recorded with a commercially available image analysis program[19]. The location and waist, ω_0, of the focus were found by fitting the data to Eq(2).

Results

Fig(2) shows the beam measured following L3 with L1, L2 and PH! removed and the spherical mirror replaced by a flat mirror. The beam is clearly astigmatic with the horizontal and vertical focuses over 3cm apart. The solid lines are least squares fits using Eq(2) to the data. To correct this astigmatism an off-axis spherical mirror is placed in the beam path. The tilt of the mirror is adjusted and measurements are made following L3 with PH1 removed until the astigmatism is corrected. Fig(3) shows the beam measured after L3 with the angle of SM optimized to 13 degrees. The horizontal and vertical focuses now focus at the same location. Notice in Fig(3), that while the astigmatism has been corrected, the beam still does not fit the gaussian beam prediction of Eq(2).

A series of two pinholes was used to make the beam fit the gaussian prediction. Experimentally it was found that one pinhole was not enough to correct the beam. A smaller pinhole will spatially filter out the spatial noise but if the pinhole is too small, then it will introduce diffraction effects such as Fresnel patterns into the beam. PH1 could not be made small enough to filter out the spatial noise without introducing diffraction effects so a second pinhole was needed. Optimal filtering was achieved with a ratio of the pinhole radius to the beam waist at focus of 1.75 for both pinholes. Fig(4) shows the beam measured after L5. The solid line is a least squares fit using Eq(2) to the data. Notice that the horizontal and vertical components of the beam focus at the same location and the data points and theory match very well.

Conclusion

An experimental method was presented to correct an astigmatic, non-gaussian beam. It was shown that an off-axis spherical mirror can be used to correct an astigmatic beam. The circularity of the beam at the off-axis spherical mirror is crucial if the astigmatism is to be corrected. In addition, two pinholes were needed to spatially filter optical noise so that the beam will focus according to gaussian optics.

Acknowledgments

This work was supported by National Science Foundation Grant No. PHY-9424637. We would also like to thank Zane Aldworth for his help.

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Figure Captions

1. Experimental apparatus used for correcting the output beam of a frequency doubled Nd:YAG laser. The schematic contains an off axis spherical mirror, SM, to correct the astigmatism in the beam, and the two pinholes (PH1,PH2) are used to spatial filter the beam.

2. Output of a frequency doubled Nd:YAG laser, with no corrections. Using equation (2) for the beam fit, we see a poor fit which we attribute to the Fresnel structure present in the beam. The beam contains a large astigmatism.

3. Output of a frequency doubled Nd:YAG laser, with astigmatism corrected by an off-axis spherical mirror. Using equation (2) for the beam fit, we see a poor fit which we can attribute to the Fresnel structure present in the beam. The astigmatism in the original output beam, Fig. 2,. has been corrected.

4. Output of a frequency doubled Nd:YAG laser, with astigmatism corrected by an off-axis spherical mirror, and spatial filtering by two pinholes. Using equation (2) for the beam fit, we see that we have a near gaussian beam with no astigmatism present.