OPTICAL CHARACTERISTICS OF ND:YAG OPTICS AND DISTORTIONS AT HIGH POWER

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Abstract

The intensity profile and beam caustics of a fiber coupled high power Nd:YAG laser beam through a lens system are studied. The thermal lensing effect and its influence on the beam profile and focal position are discussed. Asymmetry of the intensity profile in planes above and below the focal plane is demonstrated. Also the influence of small pollutions on the protective window is explained. Three different methods are used to measure the occurrence of thermal lensing and quantify these effects.

Introduction

Material processing with high power lasers is an accepted technology for some time now. The importance of thermal lensing effect on the process has been recognized as an important and sometimes critical effect for CO₂ lasers, in particular for the cutting process. In the last decade, solid state lasers, in particular Nd:YAG lasers have gained importance, especially for welding applications. As absorption of laser power in SiO₂ (Quartz) lens material is very low for the 1064 nm wavelength, thermal lensing is usually not considered to be a serious item for this type of laser.

However, with the further increase of the powers of the laser systems, there are some indications that the thermal loading of the optical system can reach levels at which more care must be taken to avoid damage to the optics, and to avoid thermal effects on the beam caustics.

In the laboratory of the Laser Technology group at the University of Twente there have been a number of situations where effects have been observed which could be explained by thermal lensing. Also process failure has occurred, which could be traced back to the failure of the fiber cap window. This motivated us to carry out a study to analyse and quantify the importance of thermal effects and the influence of small damages of optical components on the beam caustics.

Optical system

In our laboratory, research is being carried out in a wide field of laser processes. The setup for laser welding and cladding consists of a 4 kW continuous wave Nd:YAG laser (Trumpf HL4006D) as a power source. A 0.6 mm core diameter fiber transports the laser energy to the work cells. There, the fiber end is projected by an optical system onto the work piece.

The standard optical system consists of a 200 mm focal length collimator lens and, depending on the requirements, a 100, 150 or a 200 mm focus lens, producing respectively a 0.3, 0.45 or 0.6 mm diameter focus spot with a top-hat distribution (see Fig. 1).

In this paper we will concentrate on two optical windows, both added to the system to protect the vulnerable optical elements. One is a protective window close to the fiber end: the “fiber cap”. The other is the shielding glass, which protects the focus lens from damage by spatter from the process.

Fig. 1: Photo of optical system and optical layout (ray path with 100 mm focus lens).

Fiber cap damage

There are two different types of fiber connectors in use in our laboratory (see **Fig. 2**). The older type (shown left) has the fiber coming out in open air, whereas the newer fibers were delivered with a fiber cap. This fiber cap is an expendable item, which intends to protect the fiber end surface from air-born dust particles which may easily damage the heavily loaded fiber end surface. As the fiber cap window is located close to the fiber end, the intensity level is still quite high, and a small amount of pollution can easily damage the coating.

Fig. 2: Two types of fiber connectors: Old type (left) and newer type with protective cap (right).

In our laboratory, there have been a number of incidents, where the window of the fiber cap was found severely damaged, and in many cases was separated from the cap, falling down in the optical head. Inquiring with other laboratories, these incidents are not uncommon. Usually, this type of failure is noticed by lack of weld penetration, under conditions where penetration should occur normally. However, in many cases, the process window is not known yet, so recognition of a damaged fiber cap in an early stage is not evident.

It must be mentioned that in our laboratory, the exchange of fibers and optical systems occurs on a regular basis. Each time the attachment of small air-born particles to the optical surfaces may occur. Nevertheless, the initial type of change which can be noticed in the fiber cap is a uniform discoloration of the coating in the area where the beam hits the window (**Fig. 3**). In this situation there is not a clear indication of a burn-in spot at the window, so that failure by aging of the coating by the high power density might also be the cause. It must be mentioned that some of the incidents reported by other laser system owners concern systems where fibers remain on the optical head without exchanges.

Fig. 3: Photo of a fiber cap showing a start of damage on the coating.

A question, which arose in connection with this type of failure, is whether this type of failure may affect the beam caustics and intensity distribution, since some measurements have also indicated that thermal lensing may exist under some conditions. In order to investigate the effect of a damaged fiber cap, and to quantify the possible occurrence of thermal lensing, a series of experiments has been done.

Thermal lensing effect

The optical system projects the fiber end to the work piece. The optical system consists of a collimator lens to create a parallel beam from the diverging beam coming out of the fiber, and a focus lens, which refocuses the parallel beam to an image of the fiber end surface. Between the two lenses, an optional dichroic mirror is placed, which allows co-axial observation of the process (**Fig. 1**). In order to obtain a good image quality, hence minimal beam quality loss, both the collimator lens and the focus lenses consist of a combination of a strong positive lens (or even two for the 100 mm focus lens) and one weaker negative lens, both with appropriate curvatures, in order to compensate for spherical aberrations.

The thermal loading of a lens has some effects which can alter the path of the rays through the system. One effect is the expansion of the material with temperature, resulting in a shape change, and residual stresses, which may alter the refraction index. However, more important is the increase of refraction index with temperature.

This has two immediate effects (see also **Fig. 4**). The first effect is a proportional increase of the optical power (the reciprocal focal length) of each lens with the overall increase of the refraction index, caused by the overall temperature increase of the lens. Notice that both negative and positive lenses become stronger, hence partially compensate each other. The second effect is a gradual bending of the rays inside the lens material in the presence of a thermal gradient directed perpendicular to the direction of the ray.

Fig. 4: Illustration of thermal effects on a ray.

It is this second effect, which usually is the most important of the aforementioned effects, since the bending increases over the complete path length through each of the lenses. Since the rays are bended in the direction of the gradient of the refraction index, the result is a positive contribution to the optical power of each separate lens in the lens system. This is because the thermal gradient in each of the lenses is directed towards the center of the lens, considering that the energy absorbed by the lenses is mainly cooled by conduction to the house via the edges of the lenses.

It is important to realize that from the previous, it follows that the presence of a thermal gradient results in a positive lens power contribution, both for positive and negative lenses, and even for optically neutral plan-parallel plates, such as the protective windows and the dichroic mirror. As the thermal gradient increases linearly with the laser power, the thermo lensing effects can also be expected to increase proportionally with the power level.

Experimental method

In order to investigate the contribution to the thermal effects of different optical elements, different configurations have been measured (see **Tab. 1**). The configurations A, B and C are all with the same, used shielding glass, which is known to have a few burned-in spots of metal spatter (see **Fig. 18a**). The used fiber cap (configuration A) shows more visible damage (white burned-in spots) than shown in **Fig. 3**. Configurations C and D are with the same fiber, but without any fiber cap. Configuration A to D are all based on the same optical system, which has been in use for about 5 years, and some spots can be seen on the optical surfaces. In particular the collimator lens has suffered from the regular fiber exchanges that have been standard practice over the years in our laboratory. For reference, some experiments were repeated with a new optical system: configuration E.

Table 1: Tested optical configurations

Config-uration	Optical	Fiber cap	Shielding glass
A	Standard	Used	Used
B	Standard	New	Used
C	Standard	None	Used
D	Standard	None	New
E1/2	New	New	New/Used

The actual measurements were done using three different methods:

1. By measuring the beam caustics with the Primes beam scanning system.
2. By camera observations of the beam caustics passing through smoke.
3. By a simple spot shooting method.

In the next three sections, these methods will be described in more detail, and their results presented.

Method 1: Measurement with Primes system

Experimental setup

To investigate the beam caustics and the intensity distribution in the out-of-focus work planes for laser cladding, the laser beam has been analysed using the Primes FocusMonitor (**Fig. 5**). The system measures the intensity distribution by scanning with a rotating pinhole through the laser beam [1].

The optical system was placed at a fixed location, above the FocusMonitor, and the intensity distribution was measured at 15 parallel planes located at several distances from the focal plane over

Fig. 5: Primes FocusMonitor system on top of a PowerMonitor.

a total interval of 35 mm around the focus plane. At each plane a number of intensity measurements were averaged to reduce the measurement noise level. The measuring planes and windows were kept constant during all measurements, in order to avoid variations in results by the window changes, as a change of window size has an influence on the computation of the beam diameter. The measurements were performed for all the abovementioned configurations and laser powers of 500, 1000, 2000 and 3000 W. Each measurement was started about 3 minutes after the laser power was switched on, in order to guarantee that a stationary temperature profile has developed in the optical elements in the beam path.

Results

As the caustic of **Fig. 6** shows, the smallest diameter equals 0.6 mm, whereas at 16 mm above and below focus a spot of about 1.5 mm radius is obtained, all of which is expected for this optical system and beam quality.

Fig. 6: Caustic of the laser beam for the 200 mm lens.

In **Fig. 7** the intensity distribution is shown for three of the measured planes using 500 W laser power. In the left column, a colour map is presented, in the right column a cross-section of the distribution is shown. Near the focus plane the energy is uniformly distributed. At the top and bottom of the measuring range (hence about 17.5 mm from the focal plane) the energy distribution can be roughly called Gaussian shaped. This almost symmetrical behaviour with respect to the focal plane is as expected for this kind of optical systems and it represents the angular distribution by which the energy exits the fiber.

Fig. 7: Intensity distributions for configuration A at 500 W laser power at planes located above, near and below the focal plane.

Next, **Fig. 8** shows the typical planes for the measurements using configuration A with 3000 W. The figure shows that the intensity distribution above the focus has transformed from a Gaussian shape into a much more spiked shape. On the other hand, below the focal plane a ring shaped distribution is found. Comparing the distributions obtained from all measurements, it is found that the transformation from Gaussian shapes to the more peaked and ring shapes is proportional to the laser power.

Fig. 8: Intensity distributions for configuration A at 3000 W laser power at planes located above, near and below the focal plane.

Fig. 9: Intensity distributions for configuration D at 3000 W laser power at planes located above, near and below the focal plane.

Another aspect that can be clearly seen in the high power measurement, but is already present in the 500 W measurement, is the appearance of local peaks and holes in the intensity. We will come back to this in the section with the discussion of the results, where we will see that these local disturbances are related to small pollutions on the shielding glass.

For comparison, **Fig. 9** shows the results of the measurements at 3000 W with configuration D, where the disturbances by the used fiber cap and shielding glass have been cancelled by removing or replacing them.

Finally, in **Fig. 10** the effect of the power and configuration on the location of the focal position is shown, as it has been determined from the Primes measurements. The measurements were started after

Fig. 10: Position of the focus plane relative to the center of the 35 mm measuring range.

a waiting period of about 3 minutes, in order that a stationary temperature gradient has been formed. Comparing this position for all configurations and laser powers, a linear relation between used laser power and focus position, i.e. focal shift was observed, as was expected.

The figure shows that for the configuration A, a shift in focus position of about 2.2 mm between 500 and 3000 W was observed. Configurations B and C both show a shift of about 2 mm. The offset of 0.4 mm between the two lines can be explained by the fact that the removal of the fiber window changes the effective object distance, causing a shift of the image distance. From these measurements, it may be concluded that the contribution of the fiber cap to the thermal lensing is very limited, even for a damaged fiber cap.

Finally, configuration D shows a shift of about 1 mm. This shows that the pollutions on the shielding glass have a large contribution to the thermal lensing.

Method 2: Camera observations

Experimental setup

In order to get an impression of the time scale on which thermal lensing builds up, an alternative method to measure the focus shift was applied, which was based on observation by camera. To visualize the beam, smoke has been injected through the beam. The outline of the setup is shown in **Fig. 11**.

Fig. 11: Setup for the camera measurements.

A typical image obtained from these observations, demonstrating the beam caustics, is shown in **Fig. 12**. In the image also the Primes measuring system can be recognized in the background. The images were recorded with a frame rate of 2 fps for most of the experiments. The recorded images were analysed by image processing, and a Gaussian beam caustic function was fitted for each image.

Fig. 12: Typical image of the beam passing through the smoke. In the background the Primes system can be recognized.

Results

In **Fig. 13** the calculated focus position as function of time is shown for configuration A, for powers of 500, 1000, 2000 and 3000 W. The overall behaviour and amount of shift corresponds to the measured values of the Primes system (see **Fig. 10**). However, the fitted position shows quite some disturbances. This is caused by the fact that the detection of the edge of the beam depends on the local intensity of the beam to exceed the background illumination level.

There are two sources of disturbance in the present series of experiments: One is that the background was not uniformly dark, by the proximity of the Primes system. The effect on the focal position result is even worsened by the fact that the smoke observations and the Primes measurements were done simultaneously. Hence, when the Primes system starts to move after the first minutes, the background illumination changes. This is shown in **Fig. 13** as a

Fig. 13: Calculated focus position by image processing procedure.

jump at about 200 sec. The second source of disturbance is the fact that the smoke intensity did not remain constant during a measurement. The calculated focus shifts are in reasonable agreement with the Primes measurement, considering that the shift of 3 mm at 3 kW at the end of the measurement is valid at a later time than the Primes data.

Method 3: Spot shooting method

Experimental setup

As the measurement methods presented above are rather time consuming and need special equipment, our interest was also to try if it is possible to use another simple experimental method to measure thermal lensing effects. A practical method to determine the focal position at a laser work cell, is to create a line of spots with an increasing distance between the optical head and the work piece. Analysis of the burn-in spots will then indicate the position of the focus plane.

This spot shooting method has been adapted to measure the thermal effects, by extending the standard measuring procedure with the shooting of a second line of spots, immediately after the optics have been loaded for some period of time. The focal shift can then be determined by measuring the focal positions from the two neighboring lines.

Fig. 14: Experimental setup for the spot-shooting method.

The thermal loading of the lenses is done in a very simple way, by placing the optical head above a water container, such that the distance between the optical head and the water surface is at least twice the focal distance. As water is only partially transparent

for Nd:YAG, the energy is absorbed over a depth of about 10 cm. A photo of a typical experimental setup is shown in **Fig. 14**.

Results

Some typical results of the spot shooting experiments are shown in **Fig. 15** for configuration C and D, both with a 5 min. heating period of the optics at 3 kW. The lines are shot with 30 pulses with a 10 ms pulse duration and a 5 Hz repetition frequency, while the robot moves the optical system with a constant speed of 10 mm/s from right to left, and away from the target (12 mm over the length of the line of 60 mm).

Fig. 15: Partial image of two samples with the two resulting spot rows for spot shooting experiments with configurations C (upper sample) and D (lower sample). The lower rows were shot in cold condition; the upper rows were shot right after loading the optics 5 min. at 3 kW.

To determine the position of the focus plane in an accurate and reproducible manner, an image was made of the two spot lines, and the image has been processed. The calculated spot diameters show a sufficiently consistent behaviour to allow a fit of a caustic like function to determine the focal position. In this way, the accuracy of the determination of the focus position results to be of the order of 0.1 mm,

Fig. 16: Processed results of a spot experiment.

which exceeds the actual elevation distance at which the spots have been shot, which for the experiments with the 200 mm focus lens is 0.4 mm.

The spot diameters and fitted lines for the upper experiment shown in **Fig. 15** is shown in **Fig. 16**. It is found that the experiments with configuration C show a shift of 1.4 to 1.6 mm. The experiments with configuration D show a shift of 0.4 to 0.6 mm. These focus shifts are less than we observed with the other methods. This is partly caused by the fact that the heating time in the other experiments was slightly longer. Another cause is the delay of about 5 seconds between turning off the laser power and the start of the shooting of the second line. In addition, the actual shooting takes 6 seconds. As the thermal gradient in the optics is already decreasing from the moment the laser is turned off, this will lower the measured shift.

Another series of experiments was performed with configuration C and D, but now in combination with a 150 mm lens, using the same shielding glass for set C as before. For reference, experiments were repeated also for a completely new set, configuration E1 and E2, both with 150 mm focus lens. This new set was tested in combination with a new shielding glass (E1), and with the same used shielding glass (E2). The results are presented in table 2.

Table 2: Result of spot shooting experiments with various configurations and focal lengths:

Config-uration	Focal length [mm]	Shielding glass	Focus shift [mm]
C	200	Used	1.4-1.6
D	200	New	0.4-0.6
C	150	Used	0.5-0.6
D	150	New	0.2-0.3
E1	150	New	0.05-0.15
E2	150	Used	0.4-0.5

In order to see the effect of the heating time, the experiment with configuration C was repeated with different heating periods, allowing the optics to completely cool down between the experiments. In **Fig. 17** the resulting focus shift is plotted as function of the heating time of the optics. It shows that the development of the focus shift is already noticeable within a time of 30 seconds, but continues to build up in the next minutes.

Fig. 17: Influence of the heating time on the focus shift.

Discussion

Influence of a damaged fiber cap

From all the measurements presented before, the general conclusion is that thermal effects do play a role, as soon as some degree of pollution is present on the optical components.

The fiber cap does not appear to cause significant thermal lensing. This can be understood by its position close to the object. A lens close to the object or image plane acts as a field lens and will not alter much in the focal position. This does not imply that the damage to the fiber cap window does not influence the process. The high intensity, localized heating of the window causes the formation of white burn-in spots, which scatter the beam radiation. This can be noticed by an increased heating of the optical system and is confirmed by a power loss measured by the Primes PowerMonitor. This loss of power can easily cause process failure if the power loss causes the process to run out of a critical process window.

Thermal lensing and spherical aberration

The pollution of the optical elements in the imaging section, is clearly seen to cause thermal lensing, resulting in a focus shift. The most likely contributor is the shielding glass, as it is easily contaminated by spatter from the process. However, in our system, also some spots on the collimator lens have collected over the years during regular fiber exchanges, contribute to the observed thermal lensing. In fact, since the thermal lensing effect is proportional to the lens thickness, a thermal gradient in the collimator lens can be expected to cause more effect than a similar thermal gradient in the shielding glass, which is quite thin.

Depending on the precise temperature distribution inside the lenses, the thermal effects on the beam caustics can be divided into two categories: a change of the (effective) focal length and a thermally induced lens aberration. Roughly speaking, a purely parabolic temperature distribution in the lenses will lead to a shift of the focus plane, without causing optical aberrations. Any deviation from the parabolic profile will cause some form of aberration, which usually will have the form of a spherical aberration.

In a flat disk with uniform energy absorption, a parabolic temperature distribution will develop. However, the intensity distribution on the lenses is more like a Gaussian type of distribution. In addition, the spots on the collimator lens are concentrated in the center area of the lens, precisely under the fiber connector. These two factors result in a temperature distribution which shows a decreasing thermal gradient towards the outer radius. Consequently, the thermally induced bending of the rays decreases towards the larger radii, which is similar to the effect caused by spherical aberration. The asymmetry noticed in the intensity distributions in planes under and above the focal plane is precisely the type of distribution that can be expected when spherical aberration is present.

Local disturbances

If we consider the fact that the actual heat absorption is concentrated at some spots on the surface, the real temperature distribution will not be axis symmetrical, but have local spikes at the spots locations. Accordingly, the thermal gradient near a spot will be strongly influenced by the point source. Effectively, the area in the proximity of a spot can be considered as a local lens on top of the overall lens power. This results in an “image” of the spots in the intensity distributions in the planes around the focus plane. Above the focal plane (**Fig. 8**: top left intensity map), it can be noticed that the focussing effect of the mini-lenses causes “hot spots”, which coincide with the locations of the spots on the shielding glass. Similarly, in the planes below the focal plane (**Fig. 8**: bottom left intensity map and **Fig. 18c**), the rays passing near the spots have already diverged more than average, resulting in local minima in the intensity distribution.

A photo of the shielding glass is shown in **Fig. 18a**. The match between the peaks and minima and the spot positions on the shielding glass are demonstrated with a pattern which points at the most important spots. In order to show the match with the disturbances in the intensity distributions, the

distributions of the measurements with configurations A and D shown in figures 8 and 9, are subtracted from each other and plotted together with the same pattern in **Figs. 18b & 18d**. Notice that the pattern is point mirrored when passing through the focal plane. Although not all individual spots can be recognized, a good number of them can be identified.

Time behaviour

With respect to the time behaviour, we have tried two approaches to measure the build-up of focus shift as a function of time. Assuming that we have a build up of radial gradient for Fourier numbers $Fo = a \cdot t / r^2$ of the order of 0.2, we get for a beam radius of 20 mm and a diffusion coefficient for quartz of $0.87 \text{ mm}^2/\text{s}$ a

time scale of about 90 seconds.

The image processed results of the camera observations at constant power showed too much disturbance during the Primes measurement. Another smoke observation was done, where the power was switched between different levels every 100 seconds during the measurement. The result showed a combination of an instantaneous jump, followed by a gradual increase or decrease in the subsequent period, depending on the power level going up or down. The accuracy of the processed result did not allow a definite conclusion if the time behaviour can be described as an exponential approach to a stable value, but there is a tendency to become less steep towards the end of each period of constant power.

Fig. 18: **a)** Photo of the “used” shielding glass in configurations A, B, C and E2 with a pattern pointing at some typical pollutions; **c)** Intensity distribution below the focus including the same pattern (see **Fig. 8**); **b & d)** Difference in intensity of configurations A and D, above (**b**) and below (**d**) focus (see **Figs. 8 & 9**).

The spot shooting method provides some other results by which we can see a time evolution. In **Fig. 17** we have seen that there seems to be an exponential behaviour towards a final value, but the time scale seems to be considerably longer. It must be remarked that with the longer heating times, also the complete optics increases in temperature, measured outside the housing to be over 15 K for heating 5 minutes at 3 kW. This is even the case for the new and completely clean system. This temperature increase is not caused by absorption on the lens surfaces, but rather by the remaining reflectivity on each of the optical surfaces, which adds up to an estimated 5% of the transmitted power. Practically all the reflected radiation will be absorbed somewhere at the inner walls of the housing. This overall temperature change has a longer timescale, but will also have an effect on the focus position, by the fact that the average refraction index increases. Although this effect is smaller on a short term, it may surpass the effect of the radial gradient on a longer term.

Conclusions

Thermal lensing is a phenomenon which can be ignored with perfectly clean optics, but can play a role in case of damage or pollution of the optical surfaces, as it causes the lens material to heat up and build a radial thermal gradient, hence refraction index gradient. This effect already can be observed with relatively low pollution levels, when multi kW power levels are used.

The fiber cap does not contribute significantly to thermal lensing, but in case of serious damage, a power loss by partial absorption and scattering (and heating of the housing) can be noticed and will affect the process. Pollution on the shielding glass has been shown to give a major contribution to thermal lensing, which can easily go up to levels above 1 mm for a 200 mm lens.

Besides a focus shift, the thermal lensing also causes a noticeable reduction of optical image quality, by the formation of spherical aberrations. This leads to an asymmetrical intensity distribution above and below the focus. In the focal plane, the effect is limited to the effect that the edges of the top-hat spot will be more smoothed.

Even with a new fiber cap and shielding glass, we still observe a small amount of thermal lensing, which may in our experiments be explained by a small amount of pollution observed on the collimator lens used in these experiments. These damages have been

caused by the regular exchange of fibers over a period of more than 5 years.

The damaging of the fiber caps is a serious problem that seems to occur regularly. Although it can be associated with regular exchange of optics and fibers, the experience of other laser owners show that the risk of damage to the fiber caps also exists when fibers are not disconnected from the optics. As inspection is not possible without removing the fiber, it would be appropriate to develop a monitoring system which is able to detect damage on the fiber cap window, as is already available for the protective fiber window on the laser side of the fiber, and the shielding glass. An improvement of the design of the fiber connector is currently in a terminating phase [2], and the monitoring of the fiber cap has the interest of the laser manufacturer.

The spot shooting method is a simple and easily applicable method to test the performance of the optical system with respect to thermal lensing. By a simple image processing algorithm the accuracy of the method can be made surprisingly high.

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