

Spotsize measurements of a focused CW Nd:YAG laser

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Abstract

The minimum spotsize, beam quality or M^2 , and Strehl ratio of a focused laser beam provide different measures of the performance of the laser/optic system. Focusing lenses typically used to provide irradiances sufficient to cause melting and/or vaporization of metals or ceramics typically exhibit considerable spherical aberration, and thus limit the minimum spotsize attainable for a given lens at a specific laser power. The purpose of this work is to quantify the increase in the minimum spotsize and decrease in Strehl ratio of a focused materials processing CW Nd:YAG laser caused by (1) laser cavity heating and (2) spherical aberration introduced by the focusing lens. Minimum spotsize was determined by making several measurements of spotsize along the propagation direction using a scanning aperture system, and fitting the data to the laser propagation equation. These measurements were performed for 6 plano-convex lenses of different focal lengths, using laser powers ranging from 500 to 1500 watts. A nonlinear variation of spotsize with laser power and with focal length was observed for the lenses and power levels tested.

Keywords: Spotsize, beam quality, Strehl ratio, spherical aberration, thermal lensing

Introduction

Characterization of a materials processing laser is needed in order to ensure proper operation of the laser and to optimize the material process. Accurate measurement of spotsize, beam quality, and Strehl ratio are crucial to this characterization. The purpose of this paper is to outline a procedure for measurement of these three parameters for a focused CW Nd:YAG laser and to characterize these parameters as a function of laser power and focal length of the focusing lens.

Each of the three parameters (spotsize, beam quality, and Strehl ratio) have strengths and weaknesses in characterizing a laser beam for materials processing. The spotsize, and particularly the minimum spotsize, can give information about the footprint of the laser beam or the expected size of the interaction zone of the workpiece. The beam quality or M^2 provides a measure of the ability to focus the laser radiation. Lastly, the Strehl ratio can be useful in predicting actual effects, penetrations, process speeds, and applicability for a particular process (i.e. cutting, welding, drilling, vaporization, etc.).¹ This is because the Strehl gives a measure of expected peak power density at the material, as opposed to the average power or total power in the laser footprint. With knowledge of the expected peak power density and the characteristics of the material being

processed, the effect on the material can be predicted in general qualitative terms, and also in quantitative terms for some well understood processes.

The relationship between laser spotsize, divergence angle, and beam quality is given by

$$w_0 \theta = M^2 \frac{\lambda}{\pi} \quad [1]$$

where w_0 is the beam radius (spotsize), θ is the half-angle divergence, M^2 is the beam quality, and λ is the wavelength of the laser radiation, Figure 1. Spotsize is defined as the distance from the propagation axis at which the laser intensity drops to e^{-2} or 13.5% of the on-axis intensity, Figure 1. For a given laser, radiation propagating through a lens will be focused to a minimum spotsize which is limited by the unfocused spotsize of the beam, its beam quality, and any aberrating effects from the lens. For an ideal laser operating in its fundamental mode (TEM₀₀, with $M^2 = 1.0$), the minimum spotsize will be limited by diffraction. However, materials processing lasers will not operate in the TEM₀₀ mode only, but in a combination of the fundamental mode plus several higher-order modes. The beam quality and spotsize of the laser will increase as the number of modes present increases. Furthermore, both parameters will typically change with laser power due to heating of the active medium. When the active medium is

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heated, thermal blooming will occur, i.e. the active medium will develop a refractive index gradient in the plane perpendicular to the laser propagation direction. This gradient may result in a change in the beam divergence and spotsize. This effect can be minimized in fast-flow gas lasers, since heating of the active medium can be minimized by exchanging the gas in the laser cavity. However, the problem of thermal blooming in high-power solid state lasers is not as tractable, and considerable variation of laser parameters may occur as the laser power increases.

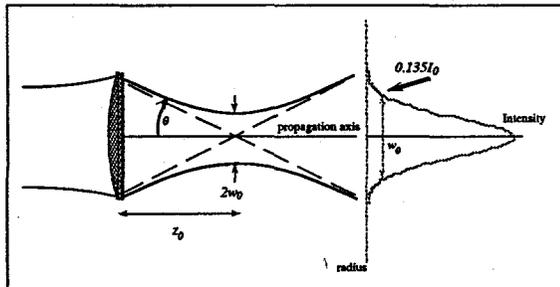


Figure 1. Propagation of laser radiation through a lens.

An increase in spotsize is also observed when laser radiation is focused by an imperfect lens. In this case, for the plano-convex lenses used, the increase is due to spherical aberration. Spherical aberration is present in any lens containing a spherical surface and results in a variation of the lens focal length with aperture. As a result, a ray propagating near the edge of the beam (large aperture) will be focused closer to the lens than a ray propagating near the axis (small aperture). This variation of focal length increases as the lens focal length decreases (corresponding to increased lens curvature). The increase in spherical aberration results in a departure of the observed minimum spotsize from the ideal diffraction-limited spotsize with decreasing focal length.

The Strehl ratio is defined as the ratio of measured or predicted peak power density to the theoretical diffraction limited peak power density for a Gaussian beam. A typical Gaussian beam is shown in Figure 1 with the $(1/e^2)$ points, and the general equation describing its shape. For a Gaussian beam, the conversion factor, $P_{0,D.L.}$, used to calculate theoretical diffraction limited peak power density (power per unit area) from the total power can be approximated using:

$$P_{0,D.L.} \sim 2 \cdot P_{Average} = P_{Total} \cdot \frac{\pi \cdot D^2}{2(f \cdot \lambda)^2} \quad [2]$$

where $P_{Average}$ is the average power seen by the workpiece, D is the lens diameter, and f is the lens focal length.

From measurement of P_0 for a particular set of parameters, the Strehl ratio can be calculated from the following:

$$Strehl = \frac{P_{0,Measured}}{P_{0,D.L.}} \quad [3]$$

M^2 and Strehl ratio utilize different relative scales ($M^2 \geq 1$ and $0 < Strehl < 1$). Furthermore M^2 is a measure of the difference in beam mode structure of a real beam from that of an ideal beam (and directly associated with spotsize or divergence as above in equation 1), and Strehl is a measure of the fractional peak intensity or power density of a real beam relative to an ideal beam. A more convenient comparison might be inverse Strehl ($1/Strehl$) and M^2 , which would put the parameters on the same relative scale. It is important to note that these two parameters do not necessarily exhibit a clear correlation (especially for a multimode laser). The only case where very close correlation would be expected is for the ideal Gaussian TEM₀₀ beam.

Experiment

The laser used in this work was a Hobart 1800 CW Nd:YAG. The cavity is a plano-plano resonator, with a rated maximum output power of 1800 watts. The laser was found to operate most stably in the range from about 500 to 1500 watts. Below 500 watts the laser beam profile possesses a large degree of asymmetry, with the asymmetric shape increasing with decreasing power. At power levels above about 1500 watts, heating of the laser rod begins to severely degrade the performance of the laser. Additionally, at each of these extremes, large fluctuations in laser beam quality and spotsize are observed. Therefore measurements were limited to power levels between 500 and 1400 watts.

Laser diagnostic measurements were performed using a Promotec Laserscope scanning aperture device. This instrument principally consists of a scanning pinhole aperture, a photodiode detector, data acquisition and storage hardware, and beam analysis software, Figure 2. The Laserscope measures spotsize by translating and rotating the pinhole through the beam, in the plane perpendicular to the propagation direction, and reflecting the radiation intercepted by the pinhole onto the detector. The detector signal is then processed and transferred to a computer. The Laserscope software then determines spotsize radius by equating the area of the beam in which 86.5 % of the total power is contained to the area of a circle. A typical data set obtained using this measurement technique is shown in Figure 3. A series of measurements are taken along the propagation direction of the laser in order to determine the minimum spotsize at a given laser power and for a given focusing lens.

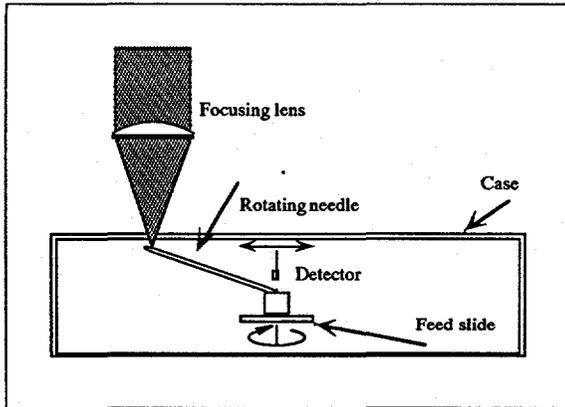


Figure 2. Schematic representation of the Laserscope scanning aperture system.

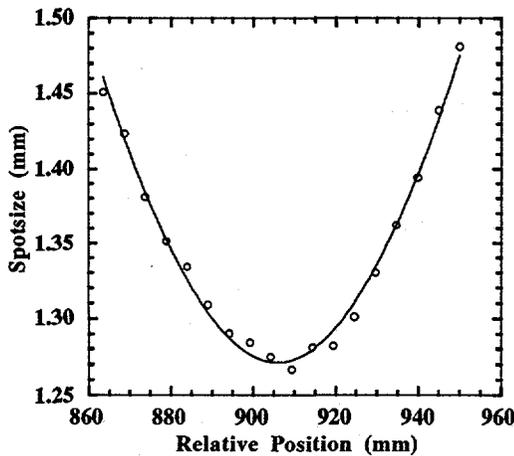


Figure 3. Typical spotsize measurements taken along the propagation direction for a 681 mm focal length lens.

These measurements were then fit to the laser propagation equation, given by

$$w(z) = w_0 \left[1 + \frac{M^4 \lambda^2}{\pi^2 w_0^4} (z - z_0)^2 \right]^{0.5} \quad [4]$$

where z_0 is the axial position of the minimum spotsize. A three parameter fit of equation [4] was used to determine w_0 ,

M^2 , and z_0 . A detailed description of this data fitting procedure is given in an earlier paper.² The stored Promotec data also contained a power profile for each measurement, including peak power, from which the Strehl ratio was derived using equation [3].

Results

Figures 4 a and b show the fitted minimum spotsize plotted as a function of laser power for 6 plano-convex lenses with focal lengths ranging from 57 to 681 mm. The value of focal length assigned to each lens was determined by substituting the values for the radius of each surface into the thin lens equation. The typical error in a measurement of spotsize was between 5-8 %. In the following graphs, the error in a measurement is approximately the same as the height of the symbol used to represent the data point.

As expected the smallest spotsize (180 μm) is obtained using the shortest focal length lens (57.4 mm), at a laser power of 570 watts. The six curves are fit to a second order polynomial, so that the curves follow a functional relationship of the form

$$w_0 = a_0 + a_1 p + a_2 p^2 \quad [5]$$

where a_0 , a_1 , and a_2 are constants, w_0 is the spotsize in millimeters, and p is the laser power in kilowatts. At $f=57.4$ mm, the variation of spotsize with laser power is relatively flat. As the lens focal length increases, the shape of the curves begins to change as the quadratic term in equation [5] begins to contribute to the minimum spotsize. At a focal length of 172 mm, the smallest spotsize is obtained at the largest power of 1490 watts. This trend continues and becomes more pronounced as the focal length increases. This effect is not understood, but may be due to differences in the amount of spherical aberration present for a specific lens positioned at a specific distance from the output mirror (longer focal length lenses are positioned closer to the laser cavity).

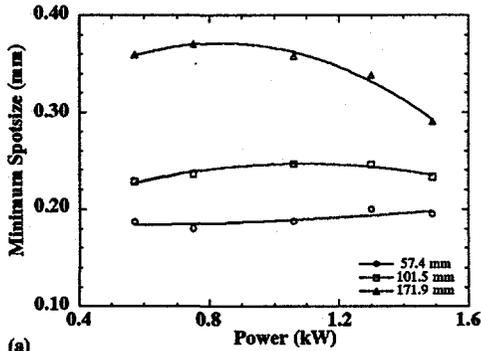
A summary of the measurements of minimum spotsize of the CW Nd:YAG used in this work is shown in Figure 5. Minimum spotsize is plotted vs. focal length for five laser powers.

Figure 6 shows the variation of minimum focused spotsize with lens focal length ($p = 740$ watts) for the six plano-convex lenses. The solid line shows the predicted spotsize for aberration-free lenses, assuming that the beam quality of the laser/optic system remains constant as the lens focal length decreases. However degradation of focusing ability with decreasing focal length has been documented for materials processing lasers/optic systems, and is believed to be due to spherical aberration.³

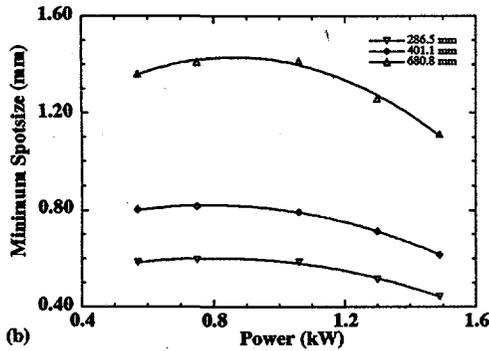
The dashed curve of Figure 5 is a nonlinear fit to the measured data points, using an equation of the form

$$w_0 = c_1 f + \frac{c_2}{f} \quad [6]$$

where c_1 and c_2 are constants, and f is the lens focal length.



(a)



(b)

Figure 4 a,b. Minimum spotsizes as a function of laser power for 6 different plano-convex lenses.

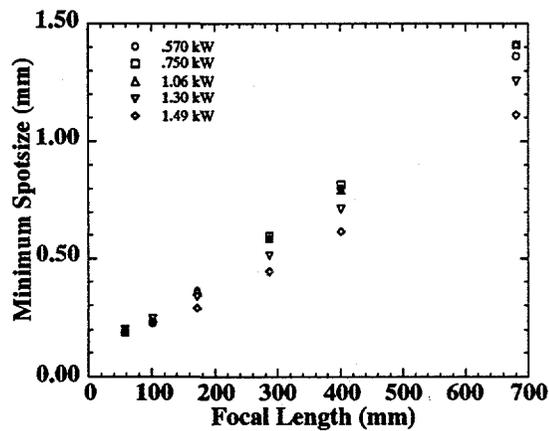
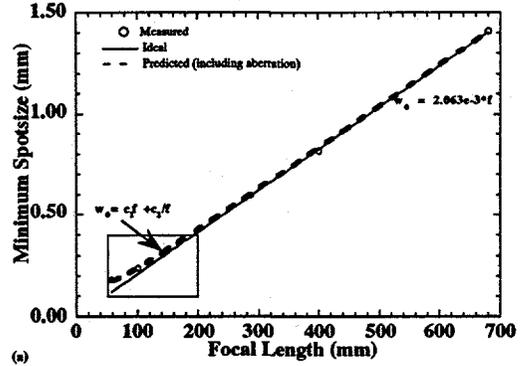
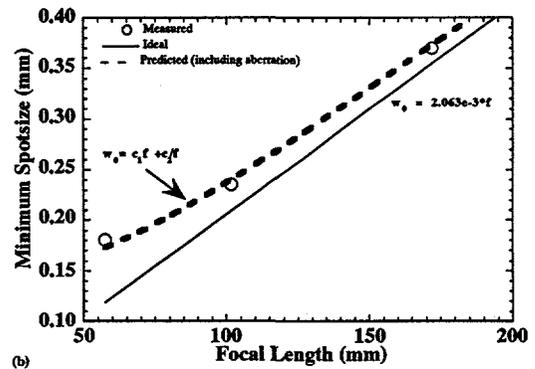


Figure 5. Minimum spotsizes of a CW Nd:YAG focused by plano-convex lenses of various focal lengths.



(a)



(b)

Figure 6. a.) Minimum spotsizes vs. lens focal length for a laser power of 740 watts. b.) Boxed section of 6a. ($c_1=2.063e-3$, $c_2=3.13 \text{ mm}^2$)

The first term of equation [6] gives the unaberrated spotsizes, and varies linearly with the lens focal length. The second term represents the contribution to the spotsizes due to spherical aberration. At long focal lengths ($f > 300 \text{ mm}$), spherical aberration is negligible, i.e., the second term is small, and spotsizes varies linearly with focal length. However as the focal length decreases, the spherical aberration term becomes important and the minimum spotsizes becomes increasingly larger than that predicted for an ideal, aberration-free lens.

Figures 7 and 8 show the inverse Strehl ratio ($1/\text{Strehl}$) versus power and focal length respectively. This Strehl ratio data was calculated using equations [2] and

[3]. There are some general similarities between the inverse Strehl ratio and the minimum spotsize data. Figure 7 showing the inverse Strehl versus power shows the maximum inverse Strehl for all power levels occurs around the 1000 W region, which is the same region where the maximum spot size occurs (see Figure 4). The rapid decrease in inverse Strehl with increasing focal length shown in Figure 8 is similar to the decrease in the contribution of spherical aberration to minimum spotsize with increasing focal length (Figure 6). In Figure 7 the inverse Strehl for all lenses has relatively high values at the shortest focal length (57.4 mm). As the focal length for a plano-convex lens increases, the inverse Strehl decreases rapidly, approaching an almost constant value for each power level. The substantial increase in inverse Strehl for shorter focal lengths is believed to be from spherical aberration, as assumed for the minimum spotsize data in Figure 6. One similarity between the minimum spotsize and inverse Strehl for the plano-convex lenses tested (and for unfocused spotsize diameters ranging from 22 to 40 mm) is that for focal lengths greater than approximately 300 mm, both minimum spotsize and inverse Strehl show no significant contribution from spherical aberration.

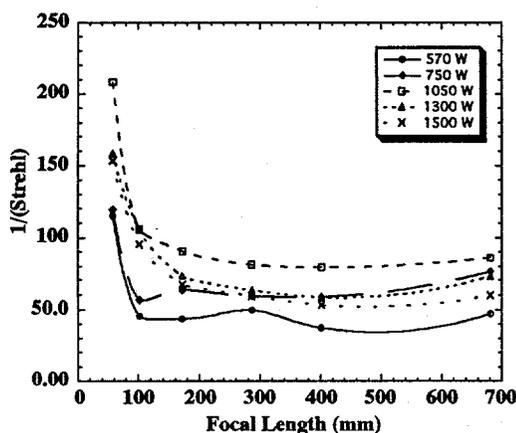


Figure 7. 1/Strehl vs. focal length. The curves are interpolations through the data points.

Discussion

The nonlinear variation of spotsize with focal length observed for the CW Nd:YAG laser and the plano-convex lenses is similar to the functional relationship determined for the same parameters for a CW CO₂ laser focused by meniscus lenses.⁴ These observations suggest that the dominant mechanism that limits focused spotsize for materials processing lasers is the intrinsic spherical aberration introduced by the focusing lens. Furthermore, the coefficient of the nonlinear term will depend only on the lens shape and the laser beam profile.

The spotsize data in Figure 4 and a plot of beam quality vs. power for a 681 mm plano-convex lens (Figure 9) show general trends that are indicative of rod lensing and resonator cavity mode effects known to develop in plano-plano cavities.⁵ To understand these effects in relation to spotsize or beam quality, the rod lensing effect must be considered throughout the power range of the laser.

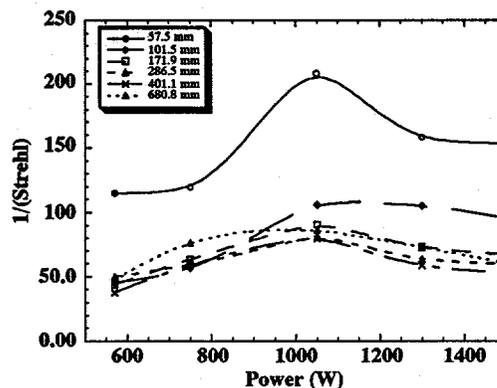


Figure 8. 1/Strehl vs. laser power with interpolated curve fits.

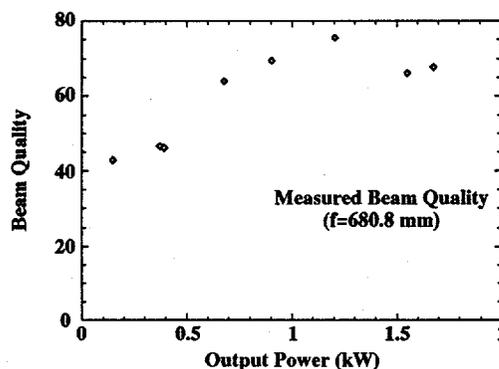


Figure 9. Variation of beam quality with laser power for a 681 mm focal length lens.

Throughout this range the radial refractive index gradient of the three rods used in the Hobart laser undergoes three distinct changes. This causes the rods to produce a lensing effect in which the effective rod focal length, f_r , decreases throughout the laser power range. By definition, the plane output mirrors act as boundary conditions and set the wavefront to a plane wave at both output mirrors throughout the laser power range. At minimum and low pumping powers the temperature gradient throughout the rod is small, and f_r is much greater than the cavity length, i.e., $f_r \gg L$. This is a region of lower M^2 , but higher instability in the

cavity. As pump power increases the effective focal length of the individual rods decrease to approximately $0.5L$. This region contains the highest observed values of M^2 , but also exhibits the greatest cavity stability (approximate confocal resonator configuration). As the pump power continues to increase, f_r continues to decrease toward $0.25L$. This last region is where M^2 starts to decrease, while cavity instability again begins to increase.⁵ Figure 9 clearly displays this variation of M^2 with power. Similarly, the spotsize data in Figure 4 for the five longest focal length lenses follow this trend throughout the laser power range.

Summary

The results of this work may be summarized as follows:

- 1.) The laser propagation equation was used to determine minimum spotsize and beam quality of a CW Nd:YAG laser.
- 2.) The variation of laser spotsize with power is quadratic in power, with the second order term becoming increasingly important at high powers and at longer focal lengths.
- 3.) The variation of minimum focused spotsize is linear at long focal lengths, and becomes increasingly nonlinear as the focal length decreases.
- 4.) The nonlinear variation of spotsize with focal length is believed to be caused by spherical aberration.
- 5.) At a laser power of 740 watts, the fitted minimum spotsize is more than 30 % larger than the ideal spotsize predicted for an aberration-free lens.
- 6.) For focal lengths less than ~ 300 mm, the inverse Strehl increases rapidly due to spherical aberration.

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