Laser Beam Characterization Results for a High Power CW Nd:YAG Laser

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ABSTRACT

In an effort to understand multimode laser beam propagation characteristics for better development of laser material processing applications, beam diagnostic experiments were performed on a 1800 watt CW Nd:YAG laser. Beam diameter data were acquired at approximately 12 positions along the beam optical axis about the minimum waist created by a long focal length single element lens at several power levels. These data were then used to evaluate the laser output beam characteristics using two differing techniques. For the ISO technique, two data points from the beam diameter data were used in determining the output laser beam characteristics. These points were the beam minimum waist diameter and the diameter at a point along the beam optical axis where the beam diameter had increased to approximately 0.7 times that of the beam minimum waist diameter. The second analysis technique involved fitting the entire data set to theoretical equations used to describe the multimode laser beam propagation and points from the fitted curve fit were then used to determine the output beam characteristics from the laser. For all power levels evaluated, calculated results predicting the laser beam minimum waist location were in agreement with measured values and more consistent using the curve-fit technique than the two-point evaluation technique.

INTRODUCTION

High power, multimode lasers have gained widespread acceptance as a tool for industrial materials processing applications. As the users of these systems seek to improve process control and product reliability, the requirements for understanding the behavior and characteristics of the laser light source continue to increase in importance. For many applications, knowledge of the laser irradiance on the work surface and how it changes away from sharp focus is critical. For example, in laser welding applications, the energy transfer efficiency is a function of the irradiance at the work surface^[1]. High reflectivity materials require a very high irradiance at the work surface to achieve efficient energy transfer into the substrate. This can be accomplished by reducing the focal length of the lens but at the cost of depth of focus and working distance. In addition, as the $f/\#$ of the lens is decreased, spherical aberration can become a dominant factor and prevent a high irradiance from being obtained^[2]. If the working distance is reduced too much, then the vapor plume generated during the welding process will deposit metal particulate onto the lens leading to scattering of the laser radiation and, eventually, catastrophic failure of the lens. In either case, the process quickly becomes unpredictable. To have a well controlled process, it is essential to be able tailor the laser beam focus properties in a predictable manner to achieve optimum results. This requires knowledge of the laser beam characteristics and methodologies to accurately predict the behavior of the multimode laser beams through space.

In the last several years, significant progress has been made in understanding the propagation of multimode laser beams through optical systems and simplifying the theory to a user friendly level^[3,4]. No longer are we required to depend on relationships solely based on diffraction limited beam propagation or forced to resort to complicated Hermite and Laguerre polynomials^[5] to describe the behavior of these multimode beams. Even better, the modified Gaussian beam propagation theory lends itself to existing beam propagation relationships such as ABCD matrices to be easily integrated into the real world.

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In an effort to develop a more fundamental understanding of the interactions occurring during laser materials processing, an extensive amount of time and effort has been invested to understand and quantify the parameters associated with multimode Nd:YAG laser beam propagation. Several methods have been reported on how to quantify the beam parameters associated with the multimode laser beams^[6] and a draft of an ISO standard defining how to make these measurements has been prepared^[7]. Now that the draft of the standard has been circulated, laser users are offering suggestions on how to modify the beam parameter measurement techniques to improve the accuracy of the measurements^[8]. In our investigation, we used both the ISO draft proposed two-point method and the suggested curve-fit method to evaluate the properties of an 1800 W CW Nd:YAG laser used in materials processing applications. The results obtained do provide insight into the best method for characterizing the laser beam parameters.

THEORY

The theory of fundamental mode Gaussian laser beam propagation is well established^[x] and methodologies (e.g. ABCD matrices)^[9] have been developed to allow these beams to be propagated through optical systems. More recently, the Gaussian beam relationships have been expanded to include multimode (or real) laser beam propagation (see Fig. 1). This development is significant since all laser beams deviate somewhat from this idealized Gaussian beam case. The relationship describing the real beam spot-size propagation is given as

$$W(z) = W_o \sqrt{1 + \left(\frac{M^2 \lambda}{\pi W_o^2} \right)^2 (z - z_o)^2} \quad (1)$$

where $W(z)$ is the real beam radius at a position z along the beam optical axis, W_o is the real beam waist radius, M^2 is the beam quality factor and z_o is the position of the beam minimum waist radius with respect to a reference position. It has been assumed in the formalization of the real beam propagation theory, that there exists an ideal Gaussian beam embedded within the real-beam propagating coaxially. Then, for the real beam, both the beam minimum waist W_o and far-field half-angle divergence Θ each deviate from the respect ideal Gaussian parameters as

$$\begin{aligned} W_o &= M w_o \\ \Theta &= M \theta \end{aligned} \quad (2)$$

where w_o and θ are the ideal embedded Gaussian beam minimum waist radius and half-angle divergence, respectively. In terms of measured parameters, then

$$\Theta = \sqrt{\frac{W_1^2 - W_o^2}{(z - z_o)^2}} \quad (3)$$

From these parameters it can then be shown that the beam Rayleigh range z_R (defined as the region near the beam waist where the beam area increases by a factor of 2 times that of the minimum beam waist area) is given by

Figure 1. Schematic representation of real-beam relationship to embedded ideal Gaussian beam.

$$z_R = \frac{W_o}{\Theta} = \frac{w_o}{\theta} \quad (4)$$

where d_o and θ are the minimum waist and divergence angle for the embedded Gaussian beam. As it turns out, the Rayleigh range is the same for both the imaginary embedded Gaussian beam and the real laser beam. This feature allows the previously developed methods for beam propagation (e.g. ABCD matrices or complex image formation equations^[10]) to be used in propagating the real beam through an optical system. Thus, if a lens system is used to produce a beam waist in space for characterization of the beam properties, the results from these tests can then be used to backwards propagate the laser beam through the optical system. This allows the laser beam diameter to be predicted anywhere along the beam optical axis and can be used to determine the output properties of a laser system. For a single element lens (see Fig. 2), backwards propagation of the real beam through the lens gives the beam waist position S_1 from the waist producing lens as

$$S_1 = f + \frac{f^2(z_o - f)}{(z_o - f)^2 + z_R^2} \quad (5)$$

where f is the focal length of the waist creating lens and z_o , in this case, is the position of the beam minimum waist from the lens. Then the beam Rayleigh range z_{R1} out of the laser cavity is

$$z_{R1} = \frac{z_R f^2}{(S - f)^2 + z_R^2} \quad (6)$$

Finally, the real beam radius W_1 and the real beam half-angle divergence Θ_1 out of the laser cavity are given by

$$W_1 = \sqrt{\frac{M^2 z_{R1} \lambda}{\pi}} \quad (7)$$

$$\Theta_1 = \frac{MW_1}{z_{R1}}$$

These relationships can then be used in determining the output parameters from a given laser system.

Figure 2. Schematic representation of the configuration used to characterize the output properties of the laser system.

EXPERIMENT

These measurements reported here are part of an effort to characterize the performance of a Martek 1800 Watt CW Nd:YAG laser system. Beamcode, a commercially available beam diagnostic system, was used to measure the focused laser beam spot size. This system uses a Cohu 6400 silicon CCD detector array as a sensor to measure the beam intensity distribution. The Cohu 6400 CCD array has a pixel pitch of less than $10 \mu\text{m}$ between pixels and the Beamcode software used a e^{-2} clip level technique to arrive at a value for the laser spot diameter. To avoid introducing aberrations into the beam, a minimum number of optical

components were used to attenuate the laser intensity and a long focal length plano-convex lens was used to create the beam waist in space. In addition, only a single lens was used to create a waist for spot-size measurements to minimize measurement errors in the location of the beam minimum waist location and cavity distance from the lens.

A schematic representation of the configuration used in performing these measurements is shown in Fig. 3. The raw output from the laser is passed through an optical attenuator assembly consisting of two 2 inch diameter fused silica optical flats which were each coated to have a reflectance of greater than 99.9% on the input side and anti-reflection coated on the second side to have transmission of greater than 99.8%. These optical elements were used to attenuate the laser energy by a factor of approximately 10^{-6} and reduce the ghost beam intensity, due to secondary reflections, to below detectable levels. The power reflected away from these optics was dumped into a water cooled sphere and baffles were used in front of the detector array to block scattered YAG light from illuminating the CCD sensor. This attenuation brought the beam down to mW levels where neutral density filters could be safely used to perform the final attenuation of laser beam to within the linear range of the detector array. A total optical attenuation of the beam of 10^{-8} to 10^{-9} was required to reduce the focused beam intensity to usable levels on the CCD array.

Figure 3. Schematic layout of the optical configuration used in performing beam analysis measurements.

After attenuation, the beam was passed through a 287 mm focal length plano-convex lens to create a beam waist in space to perform spot-size measurements on. The CCD sensor was mounted onto an x-y-z stage for alignment purposes. The stage had approximately 4" of travel along the beam optical axis to insure that an adequate range of measurements could be obtained. In addition, the travel of this axis was micrometer driven for accurate positioning of the detector array. In performing measurements, the CCD array was positioned so that the z-axis was approximately centered in its extent of travel when the sensor was positioned near the beam minimum waist location. The position of the detector array with respect to the waist generating lens was measured and all beam radius measurements were taken at positions relative to

the reference location. This position was measured carefully using a tape measure to be able to backwards propagate the beam through the optical system for determination of the output laser beam characteristics. In addition, the distance from the lens to the laser output mirror was also measured for calculation verification.

The spot-size measurements were made at five different output power levels ranging from 366 W to 1823 W. The beam radius was measured for at least 11 positions along the beam optical axis through the minimum waist region. The spot-size measurements were taken over a range until the beam nearly filled the active area of the CCD detector array. The relatively large focused spot-size of the beam limited the focal length of the lens which could be used to create the beam waist. The $f\#$ of the waist creating lens was approximately 10 in the worst case. The results from these spot-size measurements were then used in calculating the beam output parameters from the laser cavity. The calculated beam output parameters were the beam Rayleigh range, the real beam minimum waist size and location and the real beam divergence angle.

Two techniques were used in determining the output beam parameters from the laser. The first technique was similar to that described in the proposed ISO standard for beam parameter measurements. The minimum spot radius and a second beam radius along the optical axis, as well as the absolute position between the waist creating lens were then extracted from each data set. These values were input to a Mathcad (a mathematical analysis software package) file which calculated the real-beam M^2 , the beam divergence and the beam Rayleigh range. The calculated beam Rayleigh range was then used in Eqs. (5) and (6) to determine the beam minimum waist location S_1 and Rayleigh range z_{R1} on the laser side of the lens. The minimum waist radius W_1 and beam divergence Θ_1 out of the laser were determined from Eqs. (7) using the calculated beam Rayleigh range z_{R1} on the laser side of the lens.

The second technique of determining the output beam parameters from the laser involved using a curve fitting routine to fit all of the points of each data set to equation (1). The beam quality factor was taken directly from the curve-fit data. Then two points were extracted from the curve-fit corresponding to the beam minimum waist radius and a second spot radius along the beam optical axis. These values, along with their absolute position with respect to the waist creating lens, were also plugged into the Mathcad file to calculate the beam output parameters from the laser cavity. Since the laser cavity is plano-plano, it was assumed that the beam minimum waist occurred at the output coupler to satisfy boundary conditions that the beam wave front is a plane wave at this point. As a measure of merit for these results, the predicted output beam waist location S_1 was compared to the measured distance from the lens to the laser output coupler.

RESULTS AND DISCUSSION

The measured beam radius data at various positions along the lens created waist are given in Table 1. These data were taken directly from the Beamcode display of the beam data after each measurement. The radius measurements and their relative positions with respect to the waist creating lens were then used in predicting the laser beam characteristics. As previously mentioned, numerical values for the beam quality factor M^2 were obtained by two different methods: the 2-point method as defined in the proposed ISO standard and also fitting the entire data set to the theoretical relation given in Eq. 1. The results of these calculations are given in Table 2. As can be seen, the values for M^2 are generally in good agreement between the two methods; however, differences in the M^2 values do exist at various power levels, particularly at 1694 W and 1823 W. At these power levels the values for M^2 vary by approximately 6% and 19%, respectively.

The results of the fitting routine for two different power levels are shown in Fig. 4. The legends shown over the plots of the beam data in Fig. 4 display the numerical values for the beam parameters obtained

Distance From Lens (mm) Z	Measured Laser Spot Radius (mm)				
	366 W	806 W	1283 W	1694 W	1823 W
462	1.757			1.971	2.006
452	1.620	1.801	1.787	1.921	1.863
442	1.442	1.567	1.573	1.726	1.751
432	1.300	1.474	1.408	1.409	1.518
422	1.147	1.387	1.212	1.147	1.212
412	1.060	1.300	1.103	1.060	1.016
402	1.016	1.212	1.060	1.103	0.951
397				1.147	1.038
392	0.972	1.190	1.081	1.190	1.168
387	0.994	1.190			
382	0.994	1.190	1.168	1.344	1.300
372	1.016	1.234	1.300	1.453	1.475
362	1.103	1.344	1.516	1.614	1.648
352	1.234	1.518	1.723		1.802
342	1.365	1.692			
332	1.516				
322	1.665				
312	1.765				

Table 1. Measured beam radius data from the Martek 1800 Watt CW Nd:YAG laser system.

Laser Power (Watts)	Calculated Beam Parameters									
	M ²		Z _R (mm)		S ₁ (mm)		W ₁ (mm)		Θ ₁ (mrad)	
	Curve Fit	2 Point	Curve Fit	2 Point	Curve Fit	2 Point	Curve Fit	2 Point	Curve Fit	2 Point
366	57.6	56.8	315	326	943	951	2.47	2.50	7.9	7.7
806	78.2	76.0	275	335	937	911	2.62	2.94	9.5	8.8
1283	87.8	87.5	216	207	942	937	2.53	2.51	11.7	12.1
1694	98.6	104.4	202	157	930	905	2.59	2.35	12.8	15.0
1823	98.7	82.9	195	185	937	950	2.50	2.28	12.8	12.3

Table 2. Calculated beam parameters for curve-fit and two-point analysis techniques.

(a)

(b)

Figure 4. Results of curve-fit technique for (a) 1283 W and (b) 1694 W.

from the curve-fit routine. The beam minimum waist size $m1$, the beam quality factor $m2$ and the position of the minimum waist location $m3$ are derived from the fitting routine. Figure 4 (a) shows the data set taken at 1283 W while Fig. 4 (b) shows the data taken at 1694 W. As illustrated, the data set for the beam radius measurements at 1283 W fits well to the real-beam propagation model. However, the data set for the beam radius measurements at the 1694 W condition demonstrates that this is not always the case. In fact, this difference in goodness of fit is apparent by the difference in M^2 values between the curve-fit vs. the 2-point analysis techniques. As indicated by the large difference in M^2 values at the 1823 W level, the data set again does not fit the theoretical model nearly as well as at the 1283 W power level. Multiple sets of data were taken at the power levels where the fit deviated from theory with consistent results obtained each time.

In addition to the results for the M^2 values, results for the beam parameter calculations are also given in Table 2. There is no obvious difference between the two analysis techniques in values calculated for the beam Rayleigh range, minimum waist radius or the beam half-angle divergence. In addition, the values obtained for the beam waist radius at the exit mirror of the cavity are consistent with expected values. For high average powers, the Nd:YAG laser rod acts as a positive thick lens due to thermal gradients within the rod. The focal length is inversely proportional to the pump power. Although the beam output from the rod is converging, the beam wavefront curvature must match the curvature of the cavity mirrors to be consistent with boundary conditions. Since the cavity mirrors are plane, this condition is satisfied when the beam within the cavity has a plane wavefront at the mirror. That is, the beam must go from converging to diverging at this interface indicative of a minimum waist location. Since the minimum waist occurs at the laser output mirror and the beam is converging away from the laser rod, a value smaller than the diameter of the laser rod (≈ 7 mm) is expected at this location. The predicted values range from 4.6 mm to 5.9 mm.

The value from the waist creating lens to the laser output coupler S_1 (see Fig. 2) was measured to be 914 mm. The predicted values for the waist location are all approximately equal to this value within approximately 4%. The primary difference for the predicted waist locations between the two different techniques is in the consistency of the predicted values. The predict values for S_1 obtained from the curve fit data are all slightly higher than the actual measured value; however, these values are consistent within 13 mm of each other or 1.4% of the Measured S_1 value. Conversely, the predicted values for S_1 from the two-point technique vary by 46 mm or 5% of the measured S_1 value.

CONCLUSIONS

Over the last several years substantial progress has been made in understanding the propagation of multimode laser beams through optical systems and simplifying the theory to a user friendly level. No longer are we required to depend on relationships solely based on diffraction limited beam propagation or forced to resort to complicated Hermite and Laguerre polynomials to describe the behavior of these multimode beams. Even better, the modified Gaussian beam propagation theory for real laser beams lends itself to existing beam propagation relationships to be easily integrated into the real world.

The measurements we have made have allowed us to improve our understanding of the propagation of multimode laser beams through space and improve the performance of these systems for materials processing applications. We have found the real-beam propagation model to be a reliable in predicting multimode laser beam behavior through space and optical systems. The calculated values indicate that similar solutions for various beam parameters may be obtained using either the curve-fit or ISO two-point analysis techniques. However, since we have demonstrated that the curve-fit analysis technique does indeed provide more consistent solutions for the position of the waist out of the laser cavity and that all solution are consistent with expected values, we believe that it is a better technique for evaluation of multimode laser beams.

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REFERENCES

1. P. W. Fuerschbach, "Measurement and Prediction of Energy Transfer Efficiency in Laser Beam Welding", submitted to Welding Journal.
2. M. Essien and P. W. Fuerschbach, "Beam Characterization of a Materials Processing CO₂ Laser", submitted to Welding Journal Jan., 93.
3. A. E. Siegman, "New developments in laser resonators", SPIE Vol. 1224 Optical Resonators, 2-14, 1990.
4. M. W. Sasnett and T. F. Johnston, Jr., "Beam characterization and measurement of propagation attributes", SPIE Vol. 1414 Laser Beam Diagnostics, 21-32, 1991
5. Y. A. Anan'ev, Laser Resonators and the Beam Divergence Problem, Adam Higler, Bristol, 1992.
6. D. L. Wright, "Beam Widths of a Diffracted Laser Using Four Proposed Methods", Optical and Quantum Electronics, Vol. 24, 1129-1135, 1992.
7. D. L. Wright and S. Guggenheimer, "Status of ISO/TC 172/SC9/WG1 on Standardization of the Measurement of Beam Widths, Beam Divergence, and Propagation Factor", SPIE Vol. 1834 Laser Energy Distribution Profiles, 2-17, 1992.
8. R. D. Jones and T. R. Scott, "Error propagation in laser beam spatial parameters", Optical and Quantum Electronics, Vol. 26, 25-34, 1994.
9. R. L. Guenther, Modern Optics, 343-350, John Wiley & Sons, 1990.
10. M. V. Klein and T. E. Furtak, Optics, John Wiley & Sons, 1986.

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