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RESEARCH ARTICLE

Beam quality measurement and consistent safety standard for high power laser products

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Abstract With the development of laser technology, laser application technology increasingly plays a leading role in the field of industry. High power laser products and their safety requirements are attracting more attention. In laser industrial applications, laser beam quality and the system of laser beam propagation and focusing are greatly ignored. Furthermore, the basic safety standards for laser products have been neither widely publicized nor strictly enforced because of rapid development. This paper examines the underlying relationship between laser beam quality and laser manufacturing, and makes a comparison among different laser systems. It is also shown how the laser safety standards could be better understood and laser beam quality standard is advocated that directly relates to a mission requirement.

Keywords beam quality, safety standards, laser products

1 Introduction

The application of laser technology in industrial field is extensive and important. According to the power and beam quality of lasers, we can compare various laser systems. The significant goal of the development of new style lasers is improving beam quality of lasers, such as high power diode lasers and fiber lasers. Abilities of laser propagation and focus are directly dependent upon laser beam quality. A good understanding of beam quality is necessary to completely define performance capability. Most previous researches focused on laser technique itself and the analysis of materials properties after laser radiation. However, little attention has been paid to relationship between beam characteristics and laser manufacturing [1–3].

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It is recognized that safety standards of laser radiation can be helpful to promote the development of laser technology. But basic safety standards for laser products have not been widely publicized, nor strictly enforced due to the rapid development of laser technology. In this paper, an analysis and numerical calculations related to beam parameters product (*BPP*, also called K_f) to the beam propagation ratio (M^2) are presented. The laser beam qualities of different laser system are compared. Finally, the laser safety standards could be very well interpretive, and laser beam quality standard is advocated for mission requirement.

2 Methods

2.1 Measurement of beam quality

There are no uniform definition and evaluation criteria about laser beam quality because of many applications of laser technology in different fields and different fields define beam quality with different parameters including beam divergence angle, M^2, K_f, Strehl ratio, power-in-bucket, and so on [4–6].

The size of laser beam divergence angle determines how far the beam can propagate without significant divergence. The higher order mode and the greater divergence angle indicate that the beam quality is worse. However, the divergence angle can be transformed by an additional optical system, so it is not accurate that the beam quality is only evaluated by the beam divergence angle. In the fields of atmospheric optics and optical radar and communication, the parameter of Strehl ratio is used for the evaluation of beam quality. Power in the bucket is the total power within a particular area, and the size of the area is determined by two basic means: one is the actual size appropriate to a mission target; the other is a size based on the diffraction properties of the laser output aperture as the former size is not known or may be variable. The normalized power in the bucket can be calculated as the fraction of output power that ends up inside a target circle. Among parameters to assess laser beam quality, M^2 is the most popular. The following analysis will focus on M^2 and K_f to search an appropriate parameter to evaluate laser beam quality, which will meet the demand of industrial processing.

The *BPP* or K_f defined as [4]:

$$BPP = K_f = \frac{D_0 \Theta_0}{4}, \tag{1}$$

where D_0 refers to beam diameter and Θ_0 is beam divergence angle. Beam focusing characteristic parameter K_f is another way of talking about beam parameter product. K represents the beam propagation factor, subscript f indicates the focus. K_f characterizes the capacity of laser beam propagating and focusing from the view of actual application.

M^2 is an indicator of how close the beam parameter product is to the diffraction limit of a perfect Gaussian beam [4]:

$$M^2 = \frac{1}{K} = \frac{\pi}{\lambda} \frac{D_0 \Theta_0}{4}. \tag{2}$$

In fact, the border of laser beam is usually ambiguous, so calculation of beam quality is greatly dependent on the manner of defining beam widths. There can be considerable variation in measured beam quality due to distinct definition of beam widths.

Two basic means are used for defining beam widths according to ISO11145 [7]. One is encircled power (energy) width of the smallest slit transmitting $u\%$ of the total beam power (energy) in two preferential orthogonal directions x and y, which are perpendicular to the beam axis. The other is second moment of power (energy) density distribution function. In practice, in order to increase the mode volume to achieve high power, an unstable resonator structure is often used to achieve multimode output. IEC60825-1 [8] also makes provisions for the definition of beam widths. It is defined as the beam diameter d_u at a position in space is the diameter of the smallest circle which contains $u\%$ of the total laser power (energy). It is also pointed out that the second moment diameter definition is not used for beam profiles with central high irradiance peaks and a low level background, such as produced by unstable resonators in the far field: the power that passes through an aperture can be significantly underestimated, when using the second moment and calculating the power with the assumption of a Gaussian beam profile. That is to say that M^2 is inappropriate to evaluate beam quality in the field of industrial manufacturing. Evaluating beam quality in terms of M^2 for a high power laser with an unstable resonator may inaccurately estimate the ability of the laser system to accomplish its intended mission. In fact, it is extremely difficult to acquire the precision mode content and density distribution function. As to the definition of K_f and M^2, the former is a product, the later is a ratio. M^2 includes the factor of wavelength. Beam quality with various wavelengths may be significantly different even if with same value of M^2. In fact, the primary factor that determines performance of a laser system is the encircled power or energy in a small region around the focal spot. We recommend that K_f is the appropriate measure of beam quality because it is directly related to the mission objectives.

2.2 Equipments

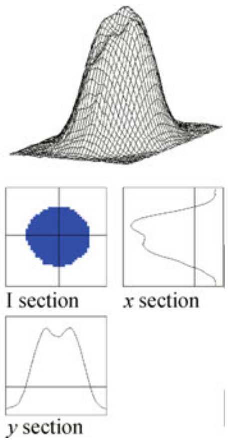
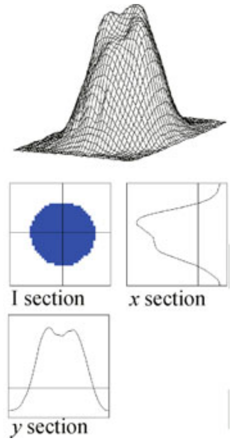
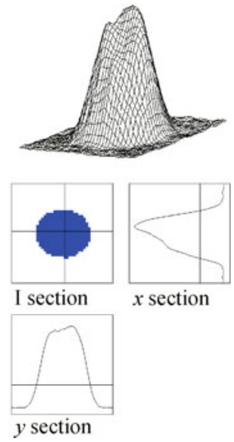
Three kinds of high power laser system are used. They are DC035 Slab CO_2 laser system, TLF6000t CO_2 laser system and CW025 YAG laser system, respectively. The high power diffusion cooling slab CO_2 laser is the best lasers with fine beam quality, the maximum output power is 3.5 kW, output mode structure close to fundamental mode of the Gaussian beam. TLF6000t CO_2 laser is a fast axial flow CO_2 laser, the maximum output power is 6 kW, radio frequency (RF) excitation, continuous or pulse output and output mode structure of transverse electric mode $(TEM_{01})^*$. The CW025 YAG laser is a lamp-pumped solid-state laser, direct current (DC) excitation, continuous or pulse output, fibber diameter of 600 μm and the maximum output power is 2.5 kW. The LASERSCOPE UFF100 is used to performing laser beam diagnostics. After measurement, the beam qualities evaluated by K_f value of these three kinds of laser system are 3.86, 8.67 and 25 mm·mrad, respectively.

2.3 Experiments

2.3.1 Ability of laser beam propagation

As the laser technology is applied in engineering practice, long-distance processing of lasers has been generally required. Different manner is used in terms of diverse wavelength. The CO_2 laser propagated through mirrors and a YAG laser propagated through optical fiber. Laser beam diameter and density distribute of the CO_2 laser always vary with optical path [6,9], which is closely associated with beam quality. Figure 1 illustrates a flying optics system. Three position are selected along x direction where the laser beam radius and density distribution are measured, results are shown in Tables 1 and 2. It is clear that the change of the former beam radius size close to 1 mm during the propagation distance of 3 m and the density distribution on beam cross-section is stable. But at the same propagation distance, the beam radius of the TLF6000t CO_2 laser is larger than 4 mm. The output mode structure is close to multimode. Besides, YAG laser propagate through fiber, the beam optical path is constant, and so its propagation ability is stable.

Table 1 Propagation properties of the slab CO_2 laser beam after flying optic system

position	I	II	III
beam radius/mm	9.407	9.74	10.34
density distribution			

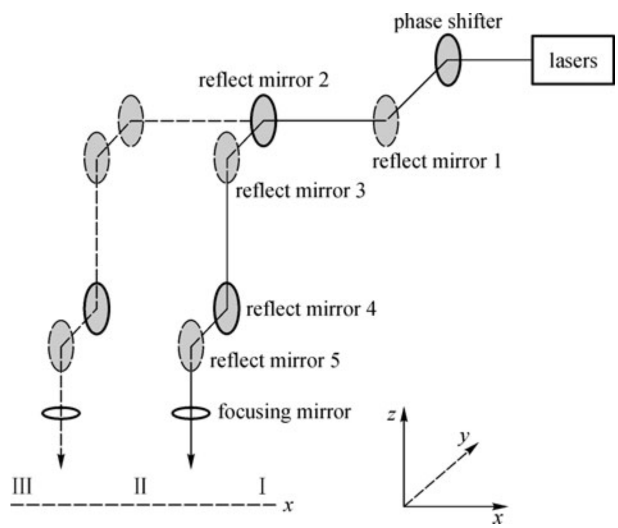


Fig. 1 Sketch of flying optics system

2.3.2 Ability of laser beam focus

Figure 2 illustrates the focusing of an arbitrary laser beam. Laser beam is focused by a lens whose focal length is f.

Focal spot (w_f) and focal depth (z_{Rf}) reflect the ability of beam focusing sufficiently. According to the law of laser optics [5,7] and Fig. 2, they can be deduced as

$$Z_{Rf} = \frac{w_f^2}{K_\mathrm{f}}, \tag{3}$$

$$w_f = \frac{2K_\mathrm{f} f}{D}. \tag{4}$$

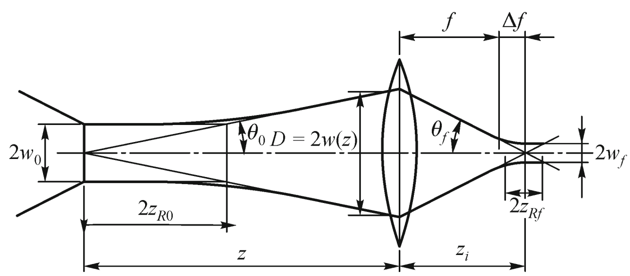


Fig. 2 Focus of an arbitrary laser beam

It is found that the beam quality and focusing system are important for the beam focusing ability. The focusing system includes focal length and the position in which mirror has been placed. To fully understand the relation between beam quality and beam focusing ability, focusing mirror with different focal lengths is used and focal beams are measured by LASERSCOPE UFF100. The results are shown in Table 3. It can be fund that the shorter of the focal length is, the smaller of the focal spot. But if the laser beam with better beam quality (lower value of K_f), a smaller focal spot can be got even with longer focal length.

3 Discussion

In order to meet the demand of laser manufacturing in a large range, the laser beam must have the ability to propagate in a large range and the stability of the beam focusing properties at the same time. On one hand, the beam quality of high power laser system primary determines whether or not laser beam can propagate, and how far can propagate. The beam quality must be specified when a laser manufacturing system is selected. It is more

Table 2 Propagation properties of the TLF6000t CO_2 laser beam after flying optic system

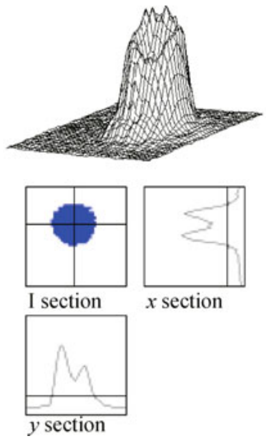
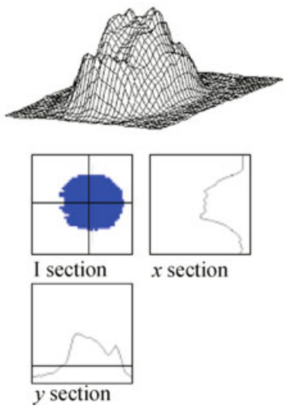
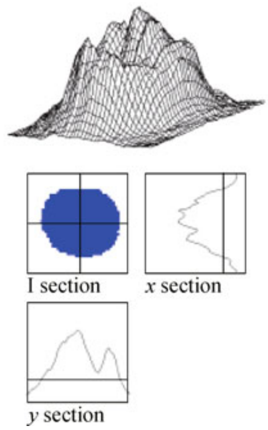
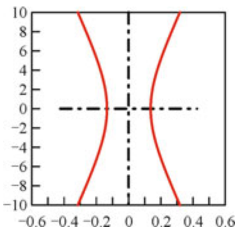
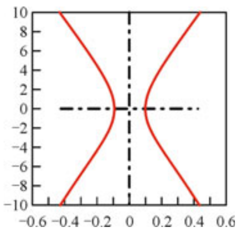
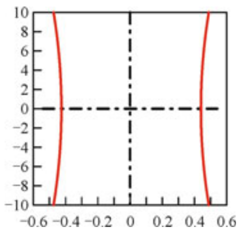
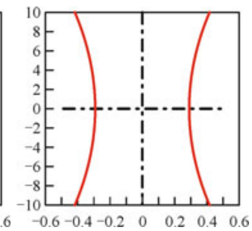
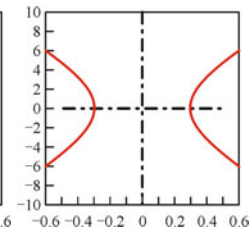
position	I	II	III
beam radius/mm	6.92	9.02	11.33
density distribution			

Table 3 Beam focusing ability with different focal lengths and different laser beam quality

lasers	DC035 Slab CO_2 laser		TLF6000t CO_2 laser		CW025 YAG laser
K_f/(mm·mrad)	3.86		8.67		25
f/mm	300	200	300	200	200
w_f /mm	0.13	0.09	0.43	0.22	0.29
z_{Rf}	4.68	2.1	21.7	9.63	3.27
simulation					

important that it meets the demand of long-distance processing. On the other hand, the changes of beam diameter and density distribution will directly affect beam focusing properties. The stability and quality of laser processing will not be guaranteed just because of this kind of changes.

The beam quality of DC035 CO_2 laser among CO_2 laser is best with K_f value is 3.86. It is clear that the change of beam radius size close to 1 mm during the propagation distance of 3 m and the density distribution on beam cross-section is stable. But at the same propagation distance, the beam radius of the TLF6000t CO_2 laser is larger than 4 mm. The output mode structure is close to multimode. So, the slab CO_2 laser is the best choice for realizing stable processing in large range.

The quality of laser manufacturing is mainly determined by the performance of laser focusing. There are two factors influencing the characteristics of high power laser beam focusing. The first one is an inherent property of the beam including beam quality; the second one is the adopted focus system including focal length and position of mirror. A lower K_f value and focus mirror, with a longer focal length or extended beam diameter could improve beam focusing characteristics effectively. In practical application, the optimal focus system can be adopted according to the beam quality of lasers, and the actual requests to obtain ideal processing quality.

A laser standard is used to ensure that laser manufacturing system will accomplish the mission requirement. But the wavelength and power of lasers are still mainly considered by laser users. How to determine whether or not laser system can meet mission requirements is unclear. Standards referring to laser technology are a small part of the criteria of laser. Furthermore, to keep up with the development of science and technology, the drafting and revising of the laser standard is a challenge. There are some basic terminology standards such as ISO11145 [7], ISO11146 [10], ISO11554 [11] and engineering standards such as IEC60825 group safety standards [8–13]. Most of those standards are adopted as national standards.

It is clear that the high power laser system needs a measurement of laser quality that is consistent with mission and meets standards. First, an ideal metric should not be subject to obfuscation or argument. Next, it should be easily made uniform for comparison between different systems. Finally, it should be directly related to mission requirements.

M^2 meets none of the described above. The parameters used to evaluate laser beam quality have been defined in industry standards, which can be a better candidate for laser standards relate to the mission requirements. If ones mission is to have very high peak irradiance without concern for anything else, then the Strehl raito is appropriate. If ones mission is to illuminate a solid angle, then, brightness is appropriate. In the high power laser industrial application, the mission is most often to deliver power to a work station. Thus, there is a requirement that we wish to get as much as power and as possible and stability from a laser beam. Each service and mission may have different standards for constructing a mission requirement and assume that these differences are appropriate. We have only recommended that the K_f is a better candidate for laser standards based on the background of industrial manufacturing. The actual approach, determined for each mission, will include information not only from laser itself, but also other environment elements and target interaction.

4 Conclusions

A definition of beam quality for high power laser manufacturing systems in the field of industrial application is suggested in this paper. Beam quality is the golden threads that run through all laser manufacturing activities. In fact, beam quality actually affects processing through propagation and focusing. Laser systems with better beam quality can assure the stability of beam widths and density distribution over a long distance. Also, the laser can be fine focusing even using a focal mirror with a longer focal length. In some cases, it can aid in meeting a special requirement such as processing in a hazardous environment. If the beam quality of laser is excellent, the high power laser system is controllable and understandable. It will use laser standard well if facing application demand directly.

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