

Investigation of the spatial structure of a high-power fiber laser beam

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Abstract. Analysis of experimental results and theoretical studies has confirmed that the free-space propagation and the transformation of a high-power fibre laser beam by an optical system can be described by the theory of laser optics. The need to use the theory of laser optics to develop modern high-performance optical systems of laser processing heads, which form the beam of the high-power fibre laser, is discussed.

1. Introduction

Laser technology widely uses fibre lasers with output radiation ranging from several kilowatts to tens of kilowatts in continuous-wave (CW) mode. These lasers are not single-mode and have a divergence of output radiation that considerably exceeds the diffraction limit [1-5].

Spatial parameters of the laser beam in the area of material processing are largely determined by the efficiency of processing operation and the implementation of its various modes. Therefore, use of an optical system that forms a laser beam with the required spatial parameters in the material processing area is imperative. Development of laser-optical systems for forming beams of coherent radiation is based on the theory of laser optics [6-9].

Powerful fibre lasers have a modular design. These lasers consist of a set of parallel active single-mode waveguides arranged within a multimode waveguide. The number of single-mode waveguides is proportional to the radiation power. For example, at a power of 4 kW there are seven single-mode waveguides. Each active single-mode waveguide radiates independently. For spatial mixing, the radiation from all single-mode waveguides is injected into a multimode waveguide called transport waveguide [1, 4, 5].

The principle of forming the radiation of high-power fibre lasers does not enable us to answer whether the propagation of a high-power fibre laser beam in free space and through an optical system can be described by the theory of laser or classical optics. Without an answer to this question, it is impossible to begin the development of modern high-performance optical systems for laser processing heads with high-power fibre lasers.

In this study, the ability to describe a high-power fibre laser beam with the parameters of the Gaussian beam, as well as the applicability of the theory of laser optics for describing the free space propagation of the beam and its transformation by an optical system, are investigated.



2. Experimental determination of the spatial parameters of a high-power ytterbium fibre laser beam

Most studies on fibre lasers consider their configurations to be characterized only by different scales of output power, as well as by the time and spectral performances of the output radiation [1-3]. The difficulty in describing the propagation of a beam of high-power fibre laser in free space and through the optical system is considered in a few studies that mainly deal with theoretical consideration and the results of numerical simulations [10, 11]. For example, Peñano J and others [11] analyse the effects arising during the propagation of a high power laser beam through the elements of an optical system and give the formulae for calculating the beam quality (parameter M^2), which takes into account the geometrical and thermal distortion of the lens optical system.

Experiments were performed with an ytterbium fibre laser of the LS-4-K series manufactured by LLC NTO "IRE-Polus" (with a maximum output power of 4 kW in CW mode and wavelength of 1070 nm). For a laser with fibre diameters of 50 μm and 100 μm , the spatial distribution of the radiation power density along the axis of the beam passing through the following components of the optical system of the laser processing head (manufactured by the German company Precitec) was measured:

- the collimating component (COL CO 30C F125 with $f' = 125$ mm, two-lens, anti-reflection coating for 1064 nm);
- the focusing component for the 50 μm fibre (YK52 with $f' = 120$ mm, two-lens, anti-reflection coating for 1064 nm);
- the focusing component for the 100 μm fibre (YC50 with $f' = 200$ mm, single-lens, anti-reflection coating for 1064 nm).

The distribution of the radiation power density was recorded by a Prometec LASERSCOPE UFF 100 laser diagnostics system at different sections of the beam. The obtained distributions of power density were used for determining the size (semi-diameter) of the laser beam by two criteria: 1) the method of moments and 2) the size of the zone concentrating 86.5% of the total flux of the laser beam. Because these criteria gave practically identical results after measurement processing, only the second criterion was used to determine the beam size in this study.

Based on the results of beam size measurements in different sections of the laser, the following spatial parameters of the laser beam were determined: the waist size, the waist position, the confocal parameter, the angular divergence, and the beam parameter product (BPP).

Measurement processing can be accomplished through various methods; for example, by the least squares method. When using this method, the results of the beam size measurement should be approximated by a hyperbolic function of the following type [12]:

$$h(z) = \sqrt{a + bz + cz^2}, \quad (1)$$

where a , b , and c are coefficients, given by:

$$\begin{pmatrix} a \\ b \\ c \end{pmatrix} = \begin{pmatrix} N & \sum_{i=1}^N z_i & \sum_{i=1}^N z_i^2 \\ \sum_{i=1}^N z_i & \sum_{i=1}^N z_i^2 & \sum_{i=1}^N z_i^3 \\ \sum_{i=1}^N z_i^2 & \sum_{i=1}^N z_i^3 & \sum_{i=1}^N z_i^4 \end{pmatrix}^{-1} \begin{pmatrix} \sum_{i=1}^N h_i^2 \\ \sum_{i=1}^N z_i h_i^2 \\ \sum_{i=1}^N z_i^2 h_i^2 \end{pmatrix}. \quad (2)$$

Here h_i is the size (semi-diameter) of the beam on the section with the coordinate z_i , and N is the number of sections in which the power density distribution was registered ($N \geq 3$).

The coefficients a , b , and c were determined and used for calculating the following beam spatial parameters:

- waist size: $h_p = \frac{\sqrt{4ac - b^2}}{2\sqrt{c}}$;
- waist position relative to the selected reference plane (taking the law of signs adopted in optics into account): $s_p = -\frac{b}{2c}$;
- confocal parameter: $z_k = \frac{\sqrt{4ac - b^2}}{2c}$;
- angular divergence: $2\theta = 2\sqrt{c}$;
- BPP : $BPP = \frac{\sqrt{4ac - b^2}}{2}$.

The angular divergence and the confocal parameters of the input beam (at the fibre output) were calculated by the formulae [1, 13]:

$$2\theta = 2 \frac{M^2 \lambda}{\pi h_p} = 2 \frac{BPP}{h_p}, \quad z_k = \frac{\pi h_p^2}{M^2 \lambda} = \frac{h_p^2}{BPP}, \quad (3)$$

where h_p is a semi-diameter of the fibre core. For a fibre laser with a fibre diameter of 50 μm and $BPP = 2$ mm·mrad (certified value), the angular divergence and the confocal parameter are: $2\theta = 0.16$ rad and $z_k = 0.31$ mm.

According to measurement results at a fibre diameter of 50 μm , the beam size on the collimating component is equal to $h_{\text{col}} = 8.6$ mm (at 86.5% of the total flux). As the confocal parameter of the beam at the output of the fibre is small ($z_k \ll 1$ mm), the beam size is given by [6]:

$h(z) = \frac{h_p}{z_k} \cdot |z - s_p| = \theta \cdot |z - s_p|$. The distance s from the fibre end to the first surface of the collimating

component is given by: $s = \frac{h_{\text{col}}}{\theta}$; its value is equal to: $s = 107.5$ mm for a fibre diameter of 50 μm . As

the front focus of the collimating component COL CO 30C F125 is located at a distance $s_{F \text{ col}} = -111.33$ mm from its first surface, the distance from the front focus to the fibre end (waist position at the optical system input) is equal to: $z_{p0} = -s_{F \text{ col}} - s = 3.83$ mm.

The spatial structure of the beam after the collimating component was also investigated. The measurements were taken for several values of radiation power (600, 900, 1200, 1800, and 2700 W) from the initial position to a distance of 100 mm, in 10 mm increments. The minimum possible distance from the last surface of the collimating component to the measurement device was equal to 45 mm. At a laser power of 2700 W and fibre diameter of 50 μm , the beam size was 9.28 mm at the initial measurement position and 9.36 mm at the final position. The power density distribution in the back focal plane of the collimating component was also recorded. The beam size in this plane was $h_{F'} = 9.34$ mm. On the basis of the principle of similitude of the optical fields in optically conjugate planes [6], the measured beam size at the back focal plane of the collimating component allows for the calculation of the angular divergence of the beam at the fibre output. Moreover, when using the 50 μm

fibre, the angular divergence of the beam was $2\theta = 0.15$ rad. It was observed that the values of the angular divergence of the fibre laser beam, calculated with both the certified data and the measurement data, practically coincide.

Figure 1 (a) shows the measured values for the beam size at the collimating component output (dotted curve) and an approximating hyperbolic function (solid curve), at a laser power of 2700 W and fibre diameter of 50 μm .

To check the validity of laser optics laws in describing the transformation of the beam of the high-power fibre laser by an optical system, power density distribution at the output of the collimating component, defocused in the longitudinal direction by $z_{\text{def}} = 15.2$ mm, were measured. In this case, the fibre end was located at a distance $z_p = z_{p0} - z_{\text{def}} = -11.37$ mm from the front focus of the collimating component. Displacement of the collimating component allowed to form a converging beam [Figure 1 (b)]. These were measured from the initial position to a distance of 70 mm for several values of radiation power (600, 900, 1200, 1800, and 2700 W).

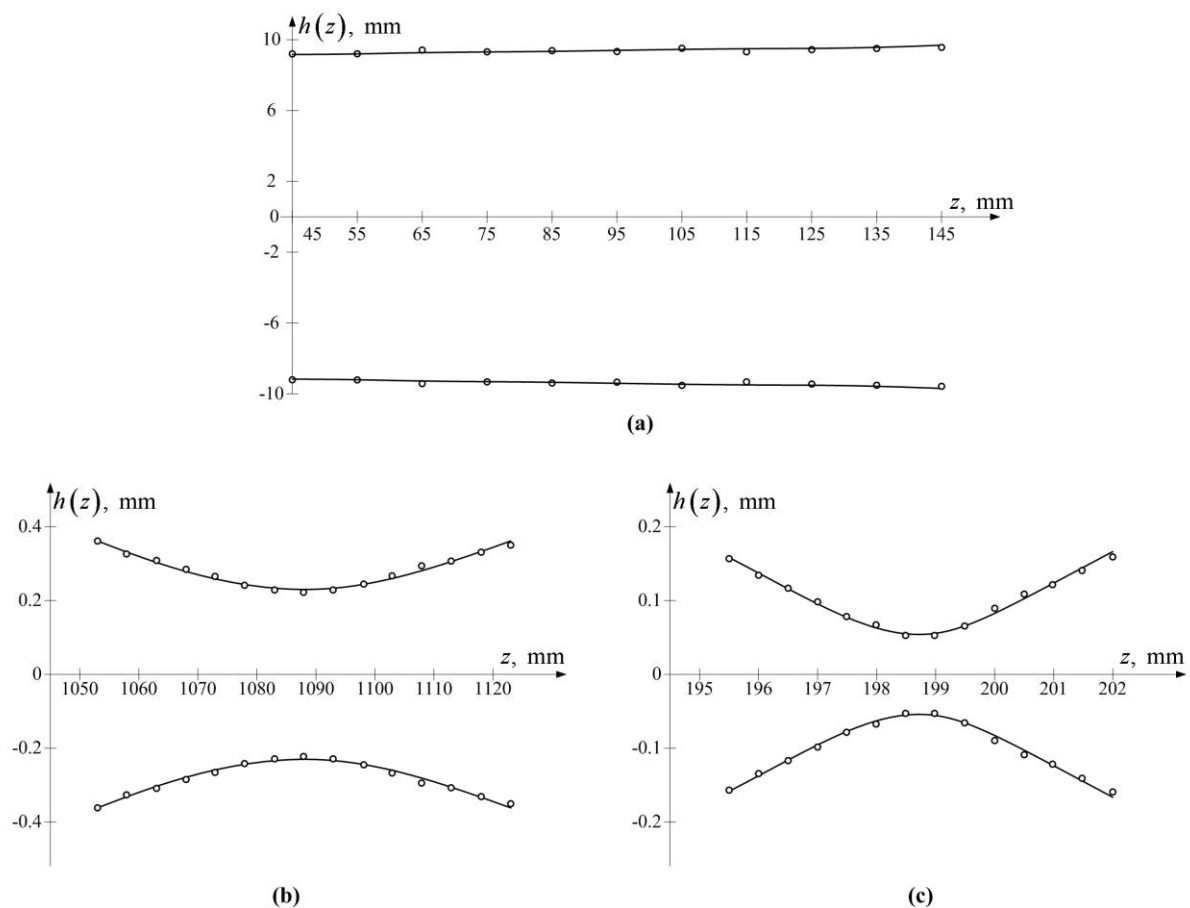


Figure 1. Beam size measurements of the laser processing head and their approximation (at a fibre diameter of 50 μm): a) at the collimating component output, b) at the defocused collimating component output, and c) at the focusing component output.

The spatial parameters of the transformed beam were calculated from the processed measurements for the case of defocused collimating component. With a laser power of 2700 W and fibre diameter of 50 μm , the spatial parameters have the following values [Figure 1 (b)]: the waist size, $h_p' = 0.23$ mm; the distance from the last surface of defocused collimating component to waist position, $s_p' = 1088.0$

mm; the distance from the back focus of the defocused collimating component to waist position, $z'_p = 963.30$ mm; the confocal parameter, $z'_k = 28.69$ mm; the angular divergence, $2\theta' = 16$ mrad; the $BPP = 1.83$ mm-mrad; and the parameter $M^2 = 5.38$.

The longitudinal magnification of a laser optical system is given by [6, 13]:

$$\alpha = \left(\frac{h'_p}{h_p} \right)^2 = \left(\frac{2\theta}{2\theta'} \right)^2 = \frac{z'_k}{z_k} = -\frac{z'_p}{z_p}. \quad (4)$$

The longitudinal magnification of the defocused collimating component had the following values, which were calculated by different beam parameters: $\alpha_{h_p} = 83.9$, $\alpha_\theta = 87.2$, $\alpha_{z_k} = 91.8$, $\alpha_{z_p} = 84.7$.

The power distribution measurements were taken for a radiation power of 600 W after focusing the components. Figure 1 (c) shows the measured values of the beam size (dotted curve) and the approximating hyperbolic function (solid curve). As a result of measurement processing, all the spatial parameters of the laser beam at the focusing component output were calculated. At a fibre diameter of 50 μm , the spatial parameters had the following values: the waist size, $h'_p = 0.054$ mm; the distance from the last surface of focusing component to waist position, $s'_p = 198.68$ mm; the confocal parameter, $z'_k = 1.13$ mm; the angular divergence, $2\theta' = 0.095$ rad; the $BPP = 2.57$ mm-mrad; and the parameter $M^2 = 7.5$.

The effect of the protective glass of the laser processing head on the parameters of the formed beam was also studied. The results obtained allowed us to conclude that the protective glass had a negligible effect on the spatial parameters and the quality of the laser beam formed in the processing area.

3. Conclusion

The multi-mode radiation of a high-power fibre laser can be described by the theory of laser optics, i.e. its free space propagation and transformation by an optical system can be described by the following spatial parameters of the laser beam: the waist size at 86.5% of the total flux, the waist position, the confocal parameter, the angular divergence. Moreover, the BPP of the fibre laser beam, calculated by the measurement data, and the certified BPP value were found to practically coincide (with less than 10% error).

Development of the optical system of laser processing head intended for forming the beam of a high-power fibre laser, should be carried out on the basis of the theory of laser optics and by recognizing that the optical elements of such a system belong to the field of power optics owing to their high power of radiation [6-9].

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