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Analyis of Fibre Laser's Optical Construction from the End of the Beam Guiding Optical Fibre to the Focal Spot

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Abstract

In material-processing fiber lasers, the resonator in the closed box produces the laser radiation. Even with the same resonator, the diameter of the laser beam transporting fiber optics and the properties of the optical elements in the laser focusing head decide the cross-section of the focused laser beam used for machining. If we summarize the formulas in different sources in the literature, we can predict the effect of each optical element: what will happen if we choose another focusing lens, put a beam expander in the system, set on the beam expander how many times the laser beam expands. The other important point is that if we want to repeat an experiment or start a production process based on a scientific publication, then in addition to the resonator, it would be good to know the data of the optical elements in the focusing head, which is usually incomplete in the presented articles, but we can determine them approximately using the four formulas listed in the article.

Keywords*: fibre laser, laser micromachining, focusing head.*

1. Introduction

Laser radiation of fibre lasers in material processing is generated by a resonator in a closed box, where laser diodes convey their energy to the excited optic fibre equipped with a Bragg grating, functioning as the reflective and the partially transmissive end mirrors of the resonator. From here, the laser delivery fibre optics transmit radiation to the focusing head. In our present article we have analysed fibre lasers used in micro-machining.

In the focusing head the laser radiation exits the laser delivery fibre optics within a given bevel angle, characterised by the numerical aperture of the optical fibre. The radiation exiting the laser delivery fibre optics is collimated by the collimator lens, followed by an optional beam expander. Then the focusing lens focuses the laser beam onto the work-piece, The relative movement of the beam to the workpiece executes the planned operation, which may be drilling, cutting, welding etc. The quantities, symbols and units of measure used in the article are shown in **Table 1** using the regular units of measurement for micro-machining, although wavelength is usually given in nanometers, and formulae (1) and (2) only provide results in micrometres if the wavelength is also given in micrometres.

In laser machining, the laser, i.e. focal spot diameter, the cross-sectional characteristic of the focused beam plays an important role, as the focused beam is the non-contact tool that performs machining through conveyance of energy. The formulae for the diameter of the focal spot are identical in several literature sources, but to achieve a common format, the radius must be doubled at times to obtain the diameter and the beam quality parameters must also be converted by entering the reciprocal value of the K beam propagation factor, i.e. M^2 beam quality factor into the formula (1) **[1, 2]**.

$$d_{f0} = \frac{4\lambda M^2 f}{B_e d_b \pi} \tag{1}$$

Here λ is the wavelength of laser radiation, f is the focal length of the lens focusing the laser beam onto the workpiece, M^2 is the beam quality factor, indicating how many times the diameter of the focal spot of the beam examined is bigger in comparison to the ideal Gaussian beam, d_b is the diameter of the close collimated laser beam before the focusing lens. If the close collimated laser beam incident on the focusing lens is expanded, the d_b beam diameter below is multiplied by the dimensionless beam expansion number (B_e), indicating the factor by which the beam diameter has been increased in comparison to the unexpanded diameter [1]. It follows from the formula for the spot diameter of the focused laser beam (1) that the smaller the value of the M^2 factor is, the smaller area the energy of the laser can be concentrated on.

The Rayleigh length is the length measured from the focal plane in the direction of beam spread, at which the area of the laser spot is doubled and the beam radius is increased by a factor of square root two, therefore the impulse energy per unit of surface area is halved in comparison to what it can be calculated in the focal spot. Generally, the beam is considered to be in focus within the double of the Rayleigh length. Its formula is very similar to that of the laser spot diameter, except that the focal length of focusing lens and the beam diameter before the lens are squared here (2) [1].

$$Z_R = \frac{4\lambda M^2 f^2}{B_e^2 d_b^2 \pi} \tag{2}$$

What further justifies this analysis is that the part of the laser beam used for laser machining is near the focal spot, and it is interesting to know where the focal spot is, what the diameter of the focal spot is and the double Rayleigh length within which it is possible to work with the laser. What further advantages does examination of the two quantities above have? Based on these two variables, the geometry of the focused beam can be described using functions: the beam diameter as a function of the z coordinate in the direction of beam propagation, with z0 being the z coordinate of the focal plane: [1].

In the literature another formula can also be found for determining the focal spot diameter of fibre lasers, in which f is the focal length of the lens focusing the laser beam onto the workpiece, d_{fc} is the core diameter of the optical fibre delivering the laser beam, and f_{coll} is the focal length of collimator collimating the laser beam (3) [3, 4]. This formula is referred by both sources of literature as approximative, so the figures obtained with their help are given to two significant figures. In another article the formula is extended by a beam expander multiplication factor, i.e. a dimensionless number(B_e) (4) [5].

$$d_{f0} = \frac{d_{fc} f}{f_{coll}} \tag{3}$$

$$d_{f0} = \frac{d_{fc} f}{f_{coll} Be} \tag{4}$$

Table 1. *Symbols, descriptions and units of measure of the quantities used in the article*

Symbols	Descriptions	Units of measure
f	the focal length of the lens focusing the laser beam onto the workpiece	mm
f_{coll}	the focal length of collimator collimating the laser beam	mm
d_{fc}	the core diameter of the optical fibre delivering the laser beam	μm
d_b	the diameter of the close collimated laser beam before the focusing lens	mm
d_{f0}	the focal spot diameter	μm
λ	wavelength of laser radiation	μm
M^2	the beam quality factor	
Z_R	Rayleigh length	μm

2. Analysis

The optical elements discussed so far and the beam path of the laser head are shown in Figure 1 with the laser head shown in Figure 2, where the laser delivery fibre optics can be seen with the yellow protective cover, as well as the focusing head with a 45 degree angle mirror, diverting the beam in the vertical direction by 90 degrees.

Even in case of identical resonators, it is the diameter of the laser delivery fibre optics and the properties of the optical elements in the focusing head that determine the cross-section of focused beam used for machining. If we summarize the formulae (1), (2), (3) and (4) found in the related literature and other sources, the effect of the particular optical elements can be predicted: e.g. what happens if another focusing lens is chosen, a beam expander is inserted into the system, or if the adjustment of this latter is modified. These changes may be necessary if the machining tasks change significantly: if a material of significantly different absorption factor, material thickness or a workpiece with different shape may have to be machined at unaltered wavelength of the laser radiation. Replacement of the focusing lens

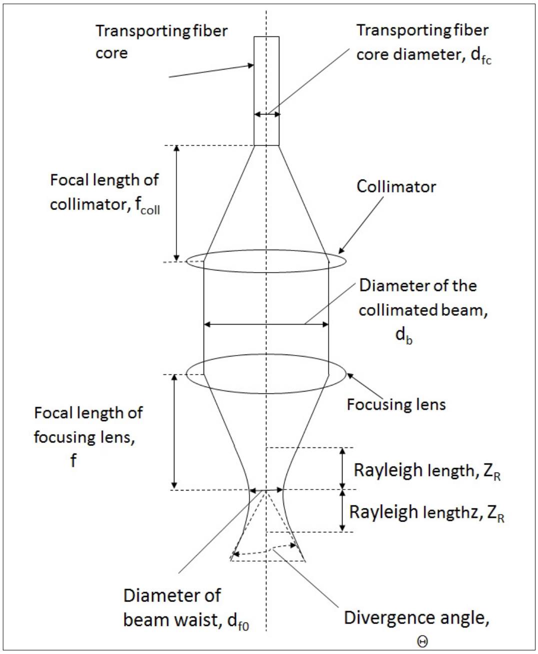


Figure 1. *Visualization of the properties of focused laser beams discussed so far.*

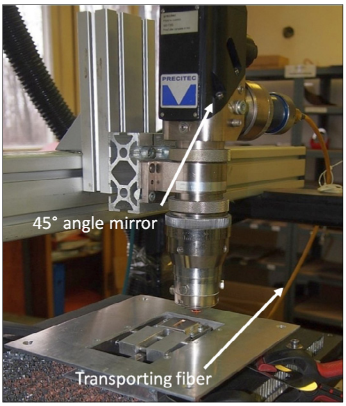
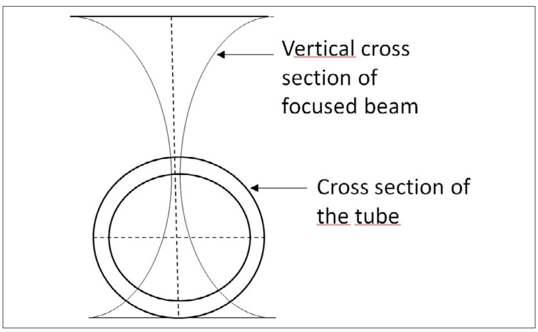


Figure 2. *The focusing head for the laser equipment.*



Fogure 3. *Longitudinal section of focused laser beam upon cutting a pipe.*

or the integration of the beam expander system can be carried out in an experimental laser arrangement, but in case of a system provided by a particular supplier such conversions must be ordered from the manufacturer, also taking into account the aspects of laser safety.

The other important aspect is if we wish to repeat an experiment or launch a production process based on a scientific publication, then it would help to know the specifications of the optical elements in the focusing head, which are usually not communicated fully in the article introduced, but which can be approximated with the help of the four formulae listed above. Articles introducing laser machining usually fail to provide the curvatures and refractive indexes of the lenses in the focusing head, therefore the beam delivery software used in the optical design cannot perform calculations due to missing input data.

Analysing formula (1), if the focal length of the focusing lens is reduced, then theoretically the spot size also decreases linearly, and it follows from formula (2) that the Rayleigh length decreases quadratically. Analysing formula (1), if expanding the laser beam by a factor of x, then theoretically the spot size decreases according to the $1/x$ function, and it follows from formula (2) that the Rayleigh length decreases according to the $1/x^2$ function. The 'theoretical' here accounts for the increase of the spherical aberration and the deterioration of the beam propagation factor when a focusing lens of shorter focal length is used, therefore d_{f0} and Z_R do not decrease so sharply, and the same happens when a beam expander is incorporated; these are analysed by Harp's article **[2]**.

Where is the significance of these factors? The smaller the spot size, the more concentrated the energy, allowing for a greater machining speed, but as the Rayleigh length also gets shorter, only thinner material can be machined this way. When it comes to cutting pipes, one application being the cutting of coronary stents, wall thickness is small, therefore a small spot size may be used, and the advantage of the small Rayleigh length in this case will be of defocusing the laser on the pipe side opposite to cutting, i.e. it will be diverged, causing no or less heat-induced transformation in the opposite wall of the pipe (**Figure 3**).

The effect of changing different lenses in the case of an identical resonator is well demonstrated by Harp's article **[2]**. Harp uses a 300 W, continuously operated ytterbium fibre laser resonator by IPG, first changing the focusing lens without beam expander, trying lenses of focal lengths of 60, 100 and 150 mm in succession, thus changing the spot size of the focused laser beam from 18.9 micrometres (for a 60 mm focusing lens) to 48.7 micrometres (for a 150 mm focusing lens). We have calculated the Rayleigh lengths: these range from 253 micrometres (for a 60 mm focusing lens) to 1582 micrometres (for a 150 mm focusing lens) (**Figure 4**). The diameter of the beam delivery optical fibre was 9 micrometres with the wavelength of laser radiation being 1075 nm, which is advisable to be substituted in the formula in micrometres. The data of the focused beam cross-section with the calculated Rayleigh lengths are shown in **Table 2**, with the data of the experiment and the laser equipment shown in **Table 3.**

In the article the change of the parameters of the focused laser beam is even more pronounced when inserting a five-fold beam expander. Thus, the spot size of the focused laser beam changes from 9.36 micrometres (for a 100 mm focusing lens) to 11.5 micrometres (for a 150 mm focusing lens). This means that the size of the smallest achievable focal spot is about half as big when a beam expander is used than without a beam expander. It must be noted that the free cross-section of the lens only allowed a 4-fold beam expansion with a 60 mm focusing lens. We have calculated the Rayleigh lengths: these range from 36.9 micrometres (for a 60 mm focusing lens) to 76.7 micrometres (for a 150 mm focusing lens) (**Figure 5**). Therefore, using a beam expander, it is possible to reduce the Rayleigh length even to one-sixth of its size, compared to the case when it is not used.

The focal length of the collimator lens - the figure for which is missing from the article - can be determined by rearranging formula (4) making fc_{oll} the subject of it. It turned out to be 28.4 mm (8) for every optical element that was tested in the article.

A particular feature of Harp's article **[2]** [2] is that it determined the focal spot diameter and the beam propagation factor by a series of welding seams on a sample of Al-7075 T6 material positioned before the laser at an angle, while varying the optical elements in the laser head.

In Baumeister's article **[6]** the following data can be found: the focal spot diameter is 20 micrometres, the wavelength of laser radiation is 1090 nm, the beam quality factor is 1.1 and the diameter of the parallel beam before the focusing lens is 5 mm, there was no beam expander, therefore the value of B_e is 1. Based on this, rearranging and making the focal length of the focusing lens the subject of formula (1), (5):

$$f = \frac{d_{f0} B_e d_b \pi}{4 \lambda M^2} \tag{5}$$

f= 65,5 mm is obtained. Notice that the formula

Table 2. *The data provided in Harp's article and the results I have calculated*

f (mm)	d_{f0} (mm)	B_e	Z_R (mm)	M^2
60	18,99	1	253,19	1,04
100	31,65	1	703,31	1,04
150	47,47	1	1582,45	1,04
60	11,08	4	36,93	2,43
100	9,36	5	41,60	1,54
150	11,50	5	76,67	1,26

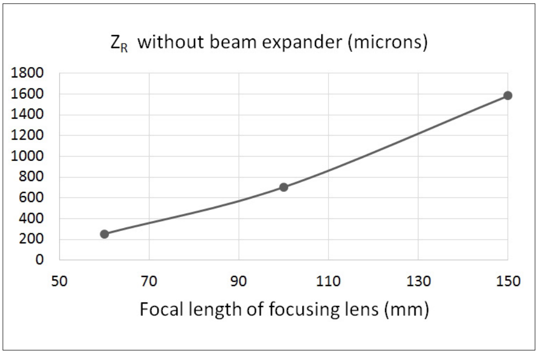


Figure 4. *Change of the Rayleigh length as a function of the focal length of the focusing lens, without beam expander.*

Table 3. *Other data of the experiment and the laser experiment*

Parameter	Value
d_{fc} (mm)	9
l (mm)	1,075
d_b (mm) unexpanded beam diameter	4,5
Manufacturer of laser equipment	IPG
Type of laser equipment	300 W, CW, ytterbium fibre laser
Machined material	Al-7075 T6
Thickness and geometry	Seams on top of the plate
Objective	Determination of laser beam cross-section near the focal point
Operation	Welding

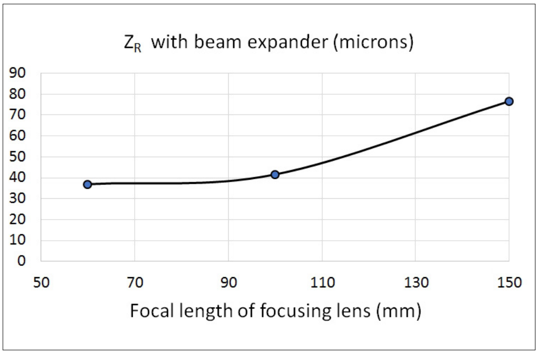


Figure 5. *Change of the Rayleigh length as a function of the focal length of the focusing lens, with beam expander.*

for focal spot diameter (1) only has to be multiplied by $f/(B_e d_b)$ to obtain the Rayleigh length from formula (2), that is (6):

$$Z_R = \frac{f}{B_e d_b} \tag{6}$$

A value of 262 micrometres is thereby obtained for Z_R. Since only a single fibre diameter is given, which is presumably that of the resonator, the focal length of the collimator cannot be calculated. The provided and calculated data are given in column 2 of **Table 4.** with the calculated values indicated by shaded backgrounds. The data of the laser and the machining are shown in column 2 of **Table 5.**

In Sobih's article [7] the focal spot diameter is 73 micrometres, the focal length of the focusing lens is f= 190,5 mm, the wavelength of laser radiation is 1090.5 nm, the beam quality factor is 1.1, with no beam expander used, therefore the value of B_e is 1. Based on this, formula (1) yields the diameter of the collimated beam before the focusing lens (7):

$$d_b = \frac{4\lambda M^2 f}{B_e d_{f0} \pi} \tag{7}$$

Using this result of 3,9 mm, , the Rayleigh length is determined from formula (6) as approximately 3.5 mm. As the core diameter of the laser beam delivery optical fibre is given as 14 mm, the focal length of the collimator lens can be calculated from formula (3), to be 36 mm (8).

$$f_{coll} = \frac{d_{fc} f}{d_{f0}} \tag{8}$$

The provided and calculated data are given in column 3 of **Table 4.** with the calculated values indicated by shaded backgrounds. The data of the laser and the machining are shown in column 3

Table 4. *The lasers examined and the machining data*

Article	Baumeister 2006 [6]	Sobih 2007 [7]	Guerra 2019 [8]	Meszlényi 2019 [9]
d_{f0} (mm)	20	73	150	14
d_{fc} (mm)	n.a.	14	150	50
f (mm)	65,5	190,5	50	50
f_{coll} (mm)	n.a.	36	50	50
l (mm)	1,09	1,07	1,08	1,07
M^2	1,1	1,1	1,1	1,1
d_b (mm)	5	3,9	0,5	5,4
Z_R (mm)	262	3554	14867	131

Table 5. *The lasers examined and the machining data*

Article	Baumeister 2006 [6]	Sobih 2007 [7]
Manufacturer of laser equipment	SPI	IPG
Type of laser equipment (all fibre lasers)	SP-100 C single-mode 100 W	YLR- 1000-SM ytterbium
Machined material	1.4301	EN 43 annealed steel
Thickness and geometry	100...300 micrometres foil	1 mm plate
Operation	foil cutting	plate cutting
Objective	narrow cutting slit: achieving a width of 20 micrometres	achieving a smooth edge of cut

Table 6. *The lasers examined and the machining data*

Article	Guerra 2019 [8]	Meszlényi 2019 [9]
Manufacturer of laser equipment	Rofin	IPG
Type of laser equipment (all fibre lasers)	FL x50s	YLR-150/1500-QCW-AC-Y11
Machined material	316 stainless steel	copper and silver foil
Thickness and geometry	pipe	50 μm copper foil, 150 μm silver foil
Operation	cutting	drilling
Objective	stent cutting	examination of drilling strongly reflective materials

of **Table 5.**

In Guerra's article **[8]** the diameter of the beam delivering optical fibre is given as 150 micrometres, the focal length of the collimator lens as 50 mm and the focal length of the focusing lens as 50 mm, and therefore the focal spot diameter can be determined from formula (3) to be 150 micrometres. Based on this and the wavelength and beam quality factor given in **Table 4.** the Rayleigh length can be calculated from formula (6) to be approximately 15 mm (no beam expander was used, hence the value of $B_e = 1$). Using the data obtained so far, formula (7) yields the diameter of the collimated beam before the focusing lens as 0.5 mm. The provided and calculated data are given in column 4 of **Table 4.** with the calculated values indicated by shaded backgrounds. The data of the laser and the machining are shown in column 2 of **Table 6.**

In Meszlényi's article **[9]** the diameter of the beam delivering optical fibre is given as 14 micrometres and the focal length of the collimator lens expanding and collimating the exiting beam is 50 mm. The focal length of the lens focusing the collimated laser beam onto the workpiece is 50 mm (f). The position of the beam expander was 1, so the multiplication factor of the beam expansion factor (B_e) is 1, and the focal spot diameter from formula (4) is determined to be 14 micrometres. Based on this and the wavelength and beam quality factor given in **Table 4** the beam diameter before the focusing lens is determined as 5.4 mm using formula (7). Finally, the Rayleigh length can be calculated from formula (6) to be approximately 131 μm. The provided and calculated data are given in column 5 of **Table 4,** with the calculated values indicated by shaded backgrounds. The data of the laser and the machining are shown in column 3 of **Table 6.**

For all the articles analysed the machined material thickness was within the depth of focus, i.e. within the double of the Rayleigh length.

3. Conclusions

In our article we have presented the method of determining the missing data from scientific publications of material machining fibre lasers, through the combined use of formulae found in various parts of the available literature. These data determine - from the exit of the optical fibre delivering the beam to the focal spot - the optical system shaping the beam placed in the machining head , and allow calculation of up to 3 of 8 missing data described in **Table 4.**

In our work the calculation of the missing factors according to various patterns, such as the focal length of the focusing lens, the focal length of the collimator, the diameter of the collimated beam, a focal spot diameter and the Rayleigh length has become possible. We have analysed the effect of changing the properties of the optical elements in the machining head on the focal spot diameter and the Rayleigh length.

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