Environment. Technology. Resources. Rezekne, Latvia
Proceedings of the 14th International Scientific and Practical Conference. Volume 3, 339-343

Optical Systems for Reducing the Divergence of Laser Beams

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***Abstract*. The rational use of lasers as sources of radiation is also related to the development of optical systems for conversion of laser radiation. One of the ways to convert the laser radiation is related to its collimation, changing the cross-section and changing the divergence. This article presents a methodology for designing two component optical systems to reduce the divergence of laser beams. Ready-made optical elements were used, with which three different configurations were created and analyzed. The optical design was developed and subsequent optimization was performed. The resulting system has diffraction-limited quality of the outgoing laser beam and small dimensions.**

Keywords: beam divergence, beam expander, laser, optical design.

I. INTRODUCTION

Laser radiation has specific properties such as coherence, high monochromaticity, high focus, high spectral and surface power. These properties of lasers allow the development of highly efficient devices and machines, fundamentally different from those operating with thermal sources of radiation [1] – [6]. In recent decades, lasers have expanded their application in technological processes related to machining of metals and alloys, such as: marking, engraving, cutting, drilling, scribing, etc.

An important part of laser technological installations is the optical system which affects the capabilities and characteristics of the entire device. Therefore, in order to use lasers rationally in various technological processes, it is necessary to develop optical systems for converting laser radiation [7], [8]. The most common way to convert laser radiation is to focus it into a spot of minimal diameter [9], [10]. Such a spot may be the waist of a beam focused by a corresponding optical system. Direct use of focusing optical systems, in most cases, does not give an optimal result. In order to obtain a spot of minimum size, it is necessary to first reduce the divergence of the laser beam and then to focus it.

II. EXPOSITION

A. Principles of focusing powerful laser radiation

For the efficient operation of the technological lasers, it is necessary that the required radiation power density in the material processing area is reached.

Changes in intensity are related to changes in the spatial width of the beam. They are caused by the diffraction and refraction of the beam by optical elements. To assess the effect of the laser radiation on the materials being processed, it is necessary to know the intensity of the beam at the focus and in the vicinity of the focus.

The transverse intensity distribution of a Gaussian beam operating in the fundamental mode TEM_{00} is given by the expression

$$I(r) = I(0) \cdot e^{-2\left(\frac{r}{\omega}\right)^2} \qquad (1)$$

where: r is a radial distance from the axis of the beam; $I(r)$ and $I(0)$ are the intensity of the beam at distance r and the axis ; ω is beam radius at which the intensity decreases e^2 times.

The beam waist at the output of the laser has a radius of ω_0 and is usually located inside the resonator. Outside the resonator, the width of the beam increases due to the increase in the distance and the diffraction. The Gaussian distribution of the beam is preserved, but divergence θ appears.

$$\theta = \frac{\lambda}{\pi\omega_0} \qquad (2)$$

Print ISSN 1691-5402
Online ISSN 2256-070X
https://doi.org/10.17770/etr2023vol3.7217
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Suppose this laser beam is focused by means of a single lens (Fig.1).

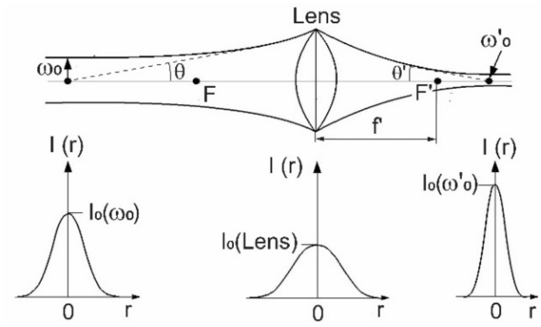

Fig. 1. The intensity distribution of a Gaussian beam before and after lens.

The diameter of the beam waist after the lens depends on the aberrations of the lens and the diffraction and is determined by the formula:

$$d_{min} = 2\omega'_0 = \underbrace{M^2 f' \frac{4\lambda}{\pi\omega_0}}_{Diffraction} + \underbrace{\frac{kD^3}{f'^2}}_{Aberration} \quad (3)$$

where: M^2 – beam quality factor; f' - focal length of the focusing lens; D – diameter of the beam entering the lens; k – coefficient dependent on the lens aberrations.

For the Gaussian beam in mode TEM_{00} $M^2 = 1$. Due to the axial propagation of laser beams, it can be assumed that off-axis aberrations are absent and only the spherical aberration is relevant. For a plano-convex lens the coefficient $k = 0{,}067$. Then from (2) and (3) it follows

$$d_{min} = 2\omega'_0 = \underbrace{2\theta f'}_{Diffraction} + \underbrace{\frac{0{,}067 D^3}{f'^2}}_{Aberration} \quad (4)$$

Expression (4) shows that there are 3 factors that affect the size of the laser spot:

- Focal length of the focusing lens f'. A decrease in f' leads to a decrease in the diffraction phenomena, and a corresponding decrease in the size of the laser spot. At the same time, as the focal length of the focusing lens decreases the spherical aberration increases. Obviously, the decrease in f' affects the spot size in various directions and at different rates. The decrease of the spot size due to the decrease of the focal length is proportional to the firs power of f'. The increase of the spot due to the increase of the spherical aberration is proportional to the second power of f'^2.

- Divergence of the input laser beam θ. A decrease in θ leads to a decrease in the diffraction phenomena, and consequently to a decrease of the size of the laser spot.

- Diameter D of the laser beam incident on the focusing lens. The increase of D has a double effect. On the one hand, it leads to an increase in the spherical aberration, and on the other hand to a decrease in diffraction.

Reducing f' is not a rational way to minimize the laser spot because it results in a decrease in the depth of the beam waist displacement, and accordingly limits the capabilities of the technological process. An effective way to achieve this goal is to use a focusing system composed of two groups. The first group simultaneously reduces the divergence and increases the diameter of the beam [11] – [14]. Generally, this is a collimating optical system. The second group focuses the laser beam thus formed into a spot of minimal size. A lens composed of one or more lenses can be used. The goal of this study is to develop a collimating system to reduce divergence of laser beams.

B. Selecting the type of the collimating system

There are two types of collimating systems, designated here as Type 1 and Type 2 (Fig. 2).

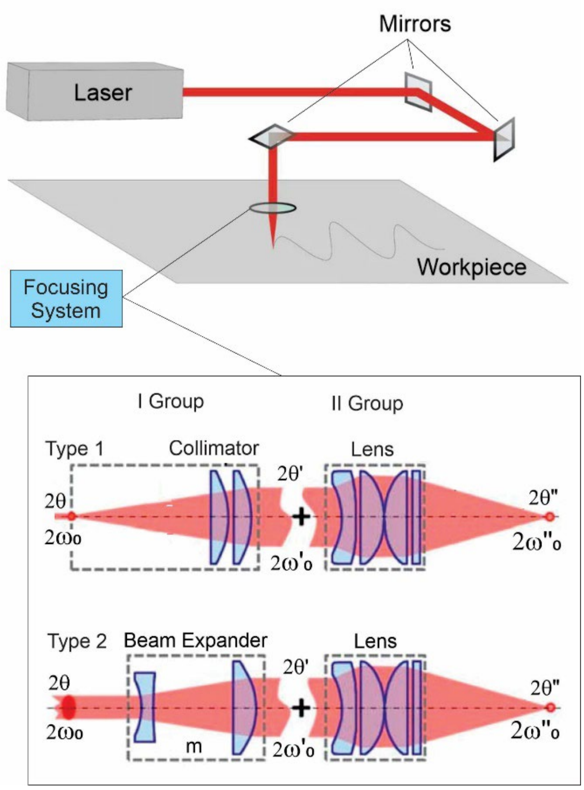

Fig. 2. Scheme of laser processing of materials.

- Type 1. A one-component collimating system, which can be composed of one or several lenses. The waist of the beam should be positioned at the front focus of the collimator. The divergence after the collimator is determined by

$$\theta' = \sqrt{\frac{2\lambda}{\pi r'_k}} = \frac{\omega_0}{f'_k} \quad (5)$$

where: r'_k - confocal parameter of the beam after the collimator; f'_k- focal length of the collimator.

It follows from expression (5) that in order to achieve low divergence, the confocal parameter must be increased, which in turn leads to an increase in the focal length of the collimator. This is an unacceptable solution because it significantly increases the overall dimensions of the system.

- Type 2. Two-component collimating system

The dimensions of the collimating system can be greatly reduced if it is made up of two components [15] – [17]. The first component focuses the beam and minimizes the size of the waist. It must therefore have a relatively short focal length f_1' . The first component can be positive or negative. The use of a negative component is preferable because it reduces the overall size of the system, the appearance of unwanted thermal phenomena is avoided due to the absence of an intermediate real image, and in such a system it is easier to correct for spherical aberration. The second component is positive. It is intended to reduce the divergence of the laser beam. For this purpose, it must first have a relatively greater focal length f_2' and secondly, be positioned so that its front focus coincides with the image of the waist from the first component.

Galileo's inverted telescopic system (beam expander) most fully meets the conditions for a two-component collimating system.

C. Development of a two-component collimating system

The beam divergence depends on the angular magnification of the collimating system MP which is determined by the ratio between the focal lengths of the two components.

$$MP = -\frac{f_1'}{f_2'} = \sqrt{\frac{z_k}{z_k'}} = \frac{\theta'}{\theta} = \frac{\omega_0'}{\omega_0} \qquad (6)$$

where: z_k and z_k' are the confocal parameters of the beam before and after the collimating system.

Expression (6) shows that in order to reduce the divergence it is necessary that $MP < 1$. This is achieved by proper selection of the focal lengths f_1' and f_2' , which results in the required ratio between the confocal parameters of the beam, which in turn causes a decrease in the divergence and an increase in the size of the beam waist after the collimating system.

Expression (6) is true for a precisely focussed Galilean telescopic system, i.e. for one where the back focus of the first component coincides with the front focus of the second component. Strictly speaking, after the first component of the collimating system the waist of the beam does not coincide with its back focus. Therefore, to minimize the divergence it is necessary to defocus the Galilean system and place the front focus of the second component at distance Δ from the back focus of the first component, so that it coincides with the image of the waist from the first component:

$$\Delta = z_1' = -\frac{z_1 f_1'^2}{z_1^2 + z_{k1}^2/4} \qquad (7)$$

where: z_1 – distance from the beam waist after the laser to the front focus of the first component of the collimating system; z_1 – distance from the beam waist after the first component to its back focus; z_{k1}^2 – confocal parameter before the collimating system.

It is assumed that the type of the laser and its parameters are known: λ, $\omega_0 = \omega_1$, $\theta = \theta_1$, $r_k = r_{k1}$. The design of the two-component collimating system was developed in the following sequence:

a) Determining the angular magnification MP by expression (6).

b) Determining the diameter D_1 of the first component.

$$D_1 \geq 2\omega_0 \sqrt{1 + \frac{2s_1}{r_k^2}} \qquad (8)$$

where s_1 is the distance between the laser waist and the principal planes of the first component of the collimating system.

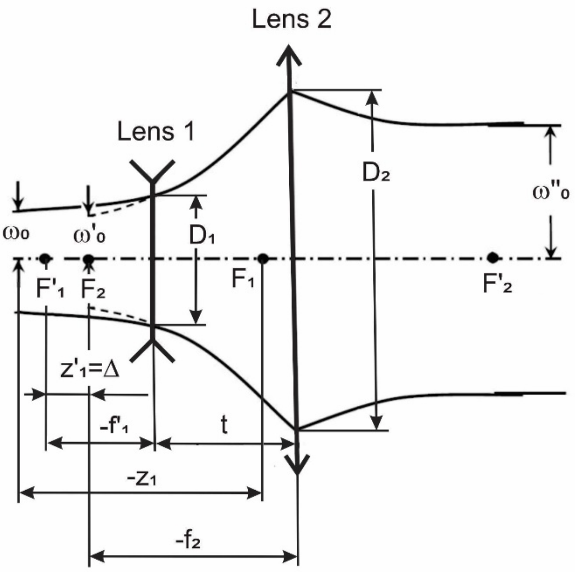

Fig. 3. Scheme of laser processing of materials.

c) Determining the focal length of the first component f_1' so that, for aberration reasons, the focal number of the collimating system meets the condition $F/N > 4$.

d) Determining the defocus of the Galilean system by expression (7).

e) Determining the confocal parameter of the beam r_{k1}' after the first component

$$\mathrm{r}'_{k1} = \frac{r_{k1} f_1'^2}{z_1^2 + {z_{k1}^2}/{4}} \qquad (9)$$

f) Determining the beam waist ω'_{01} after the first component

$$\omega'_{01} = \sqrt{\frac{\lambda r'_{k1}}{2\pi}} \qquad (10)$$

g) Determining the focal length of the second component f_2'

$$f_2' = \frac{f_1' r_{k1}}{MP\sqrt{4z_1^2 + r_{k1}^2}} \qquad (11)$$

h) Determining the diameter D_2 of the second component

$$D_2 = 2\omega'_{01}\sqrt{1 - \left(\frac{2f_2'}{r'_{k1}}\right)^2} \qquad (12)$$

D. Results

A two-component collimating system was developed for a Nd-YAG laser with a wavelength $\lambda = 1{,}064\ \mu m$ and a beam waist diameter $2\omega_0 = 3\ mm$. The angular magnification of the collimating system is $MP = 0{,}2^x$, which results in a 5 times increase in beam width .

In order to simplify the design and reduce the price, ready-made optical elements [18], [19] from the Edmund Optics catalog were used. For Lens 1 and Lens 2 from Fig. 3 are chosen negative plano-concave and positive plano-convex singlet respectively. To reduce spherical aberration, rays enter the lenses through their flat surfaces. Three configurations of collimating systems have been developed that use lenses with different focal lengths. These configurations are optimized using the OSLO optical software.

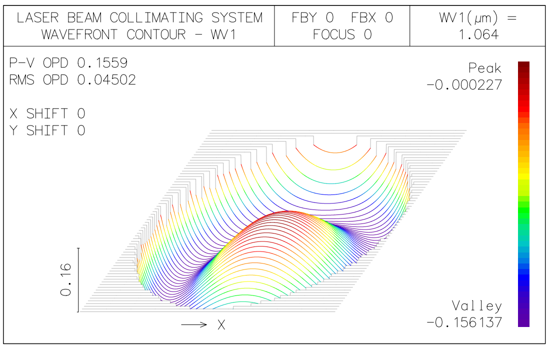

Fig. 4. Wavefront analysis of configuration 2.

The distance between Lens 1 and Lens 2 was used as a variable parameter. The distance t and the total length of the collimating system L were determined taking into account the actual thickness of the lenses. As an optimization criterion were used the RMS wavefront error (Marechal criterion), the peak-to-valley (P-V) wavefront error (Rayleigh criterion) and RMS spot size in the image plane (Airy disc criterion).

TABLE 1 THE PARAMETERS OF THE THREE CONFIGURATIONS COLLIMATING SYSTEMS

Configuration		1	2	3
Lens 1	***f_1', mm***	-12	-12	-24
	D_1, mm	6	6	12
	Catalog №	#45-008	#45-698	#45-016
	Glass	N-BK7	Si	N-BK7
Lens 1	***f_2', mm***	60	60	120
	D_2, mm	25	25	30
	Catalog №	#45-127	#45-127	#45-243
	Glass	N-BK7	N-BK7	N-BK7
Collimating system	***t, mm***	45,72	45,79	93.9
	L, mm	51,92	52,49	103.4
	W_{RMS}, waves	0,08024	0,04502	0,008107
	Marechal criterion	0,071	0,071	0,071
	W_{P-V}, waves	0.2612	0,1559	0,02675
	Rayleigh criterion	0.25	0.25	0.25
	Spot radii β_{RMS},mrad	0,139	0,065	0,019
	Airy radii β_{Airy},mrad	0,084	0.083	0.086

$$\left.\begin{array}{ll} \text{Rayleigh criterion} & W_{P-V} < \frac{\lambda}{4} \\ \text{Marechal criterion} & W_{RMS} < \frac{\lambda}{14} \\ \text{Airy disc criterion} & \beta_{RMS} << \beta_{Airy} \end{array}\right\} \qquad (13)$$

In table. 1 shows the parameters of the three configurations and the results of their evaluation according to these criteria.

- The worst quality is in the configuration 1, which is made up of lenses with small focal lengths. This configuration does not meet any of the criteria (13)
- In configuration 2, the first lens is Fused Silica. This is a compact system with the same small focal lengths.
- Configuration 3 scores many times over criteria (13), but its dimensions are the largest.

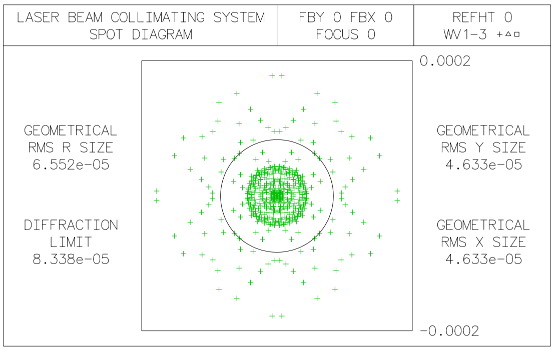

Fig. 5. Spot diagram analysis of configuration 2

Table 1 shows that configurations 2 and 3 are diffraction limited. Configuration 2 can be accepted as optimal. In Fig. 4 and Fig. 5 is shown evaluation of its wavefront and spot diagram.

III. CONCLUSION

The principles of laser beam focusing are investigated. For increasing the intensity of the laser beam into a small spot, it is first necessary to expand it and reduce its divergence. A two-component collimating system has been developed, which is based on Galileo's inverted afocal system. Ready-made optical elements were used, with which three different configurations were created and analyzed. The resulting optical systems are optimized to minimize the peak-to-valley (P-V) wavefront error, RMS wavefront error and the RMS spot size. Configuration 2 was chosen as optimal because it fulfills these quality criteria and at the same time the focal lengths and dimensions are small.

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