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Design and simulation of an optical system of high-power fiber-coupled laser module

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Abstract: The paper presents the simulation results for an optical system based on a high-power and high-brightness laser module. The module design implies spatial and polarization combining of beams from 24 single-emitter laser diodes. The theoretical design and computational simulation were conducted for the fiber-coupled optical system with the fiber of 200/225 μm in diameter and numerical aperture of 0.22. The coupling efficiency is 89% which correlates with the results of experiments with the laboratory module prototype.

Keywords: laser-based diode module, coupling, optical system, spatial combining of beams, polarization combining of beams

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Расчет и моделирование оптической системы высокомощного лазерного модуля с волоконным выводом излучения

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Аннотация. В работе представлены результаты моделирования оптической системы лазерного модуля с высокими показателями мощности и яркости излучения. Произведен теоретический расчет и компьютерное моделирование оптической системы ввода излучения в волокно диаметром 200/225 мкм с числовой апертурой 0,22. Эффективность ввода лазерного излучения в волокно составляет 89%.

Ключевые слова: лазерный диодный модуль, ввод лазерного излучения в волокно, оптическая система, пространственное объединение излучения, поляризационное объединение излучения

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Introduction

Fiber-coupled laser modules (LMs) are mostly used as highly efficient sources for high-power fiber and solid-state laser pumping and also can be applied in material processing, medical equipment, and scientific studies.

The development and enhancement of laser technologies imposes the need in continuous power growth of fiber-coupled laser modules.

Both single-emitter laser diodes (LDs) and laser diode bars (LDBs) can be applied as radiation sources in laser modules. LDBs have the advantage over LDs due to the small number of elements and sufficiently high output power [1]. The principal constraining factor during LDB coupling is implied by the high degree of radiation astigmatism. Radiation reconfiguration systems based on microoptic elements (mirrors, cylindrical lenses, and prisms) are utilized to compensate the beam asymmetry along the fast and slow axes [1, 2]. Complex microoptics requires high shape accuracy, high surface quality and minimization of transition regions between the elements. In combination with significant mounting efforts it causes high cost of such transducers and is appropriate only for systems with a constrained number of LDBs. Besides, LDBs have another disadvantage: the bar 'smile' affects the radiation quality and increases the focused beam size.

LD-based modules are the most preferred radiation sources due to their high capacity, brightness, and efficiency. The opportunity to use optical elements for each emitter enables to form high-quality radiation with a dense beam packing, while the optimal design of the focusing system provides high coupling efficiency. The references [3, 4] present the developed LM based on spatial combining of beams from six or seven single-emitter LDs. In the given framework the above designs were applied as a prototype to develop a module with the power of > 350 W. Besides the spatial combining, polarization beam combining was also used. The work presents the computational simulation results for the module optical design.

Optical system design

Table 1 shows the LDs parameters for the task to develop a LM over 350 W with 200 μm/NA 0.22 fiber.

Table 1

Laser diodes characteristics

Parameters at 22 A and 25 °C	Value
Operating voltage, V	1.65
Laser radiation power, W	21
Center wavelength, nm	915 ± 5
Polarization (TE)	98%
Emitter width, μm	190
Beam divergence at the level of $1/e^2$ along the fast axis, °	27.4
Beam divergence at the level of $1/e^2$ along the slow axis, °	5.5

Obtaining a high-quality beam corresponding to the fiber parameters is the key challenge during spatial combining of beams from single-emitter LDs.

Beam parameter product (BPP) is used to evaluate the beam quality:

$$BPP = \frac{\theta \cdot D}{2},$$

where D is the waist width, and θ is the beam divergence. BPPs of the selected diodes radiation are BPP_{FA} = 0.42 mm·mrad and BPP_{SA} = 8.6 mm·mrad for the fast and slow axes, respectively.

The limit number of diodes in the spatial combining of beams design is restricted by the fiber BPP:

$$BPP_f = \frac{\theta_f \cdot D_f}{2} = 22 \quad \text{mm} \cdot \text{mrad},$$

where D_f is the fiber core diameter, and θ_f is the fiber numerical aperture. The maximum LD number along the fast and slow axes cannot exceed the following value in the spatial combining of beams design in case of complete beam coupling with the fiber:

$$N_{FA,SA} = \frac{BPP_f}{2BPP_{FA,SA}} \gamma_{FA,SA},$$

where $\gamma_{FA,SA}$ is the filling factor along the fast and slow axes, respectively. The choice of 1 LD along the slow axis and 12 LDs along the fast axis completely satisfies the requirement.

Besides spatial combining, polarization combining of beams of two LD arrays with 12 pieces in each (Fig. 1) is used to increase the output power of the module.

LDs are stepwise positioned with a shift of 0.5 mm in vertical plane and of 4.5 mm in horizontal plane.

The beams from each LD (Fig. 1, item 1) are collimated using cylindrical lenses (Fig. 1, item 2), and then, reflected from the mirrors (Fig. 1, item 4), they are formed in a combined beam, consisting of vertical beams. The polarization direction of the second LD array is changed by 90° using phase half-wave plate (Fig. 1, item 5). The PBS (Fig. 1, item 7) combines the radiation with two perpendicular polarization directions. Finally, a specially designed focusing system (Fig. 1, items 8, 9) enables the formed beam to couple into the fiber (Fig. 1, item 10).

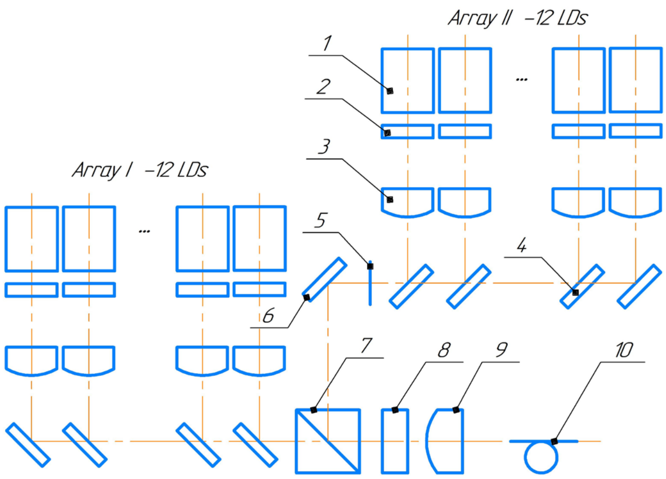

Fig. 1. Basic optical design of the laser module: LD *1*, acylindrical micro lenses *2*, cylindrical lenses *3*, rotating mirrors *4*, half-wave plate *5*, rotating mirror *6*, polarized beam splitter (PBS) *7*, focusing lenses *8*, *9*, and optical fiber *10*

Results and Discussion

The following expression describes the laser beam spatial parameters at the output of the ideal optical system [5]:

$$\alpha = \frac{z'_k}{z_k} = \frac{z'_p}{z_p} = \left(\frac{\theta}{\theta'}\right)^2 = \left(\frac{r'_p}{r_p}\right)^2 = \frac{f'^2}{z_k^2 + z_p^2},$$

where α is the coefficient of the longitudinal increase of the laser optical system; z_k, z'_k are the confocality parameters of the input and output beams; $z_k = r_p/\theta$, $z'_k = r'_p/\theta'$; z_p, z'_p are the segments, determining the waist plane position of the initial and transformed beam relative to the front and back element focuses; and $2r_p$, $2r'_p$, θ, θ' are the beam diameter in the waist cross-section and the angle divergence before and after the transformation, respectively. The given ratio was used to design the overall parameters of the optical system with the required output beam parameters corresponding to the fiber parameters.

Computational simulation was used to analyze and optimize the optical system with the consideration of spherical aberrations and beam defocusing of each emitter.

Two orthogonal lenses provide successive fast and slow axis radiation collimation. The acylindrical fast axis collimation lens (FAC lens) with a focal length of 0.3 mm is used for beam pattern narrowing along the fast axis, and cylindrical slow axis collimation lens (SAC lens) with a focal length of 13 mm is used for laser radiation collimation along the slow axis (Fig. 2).

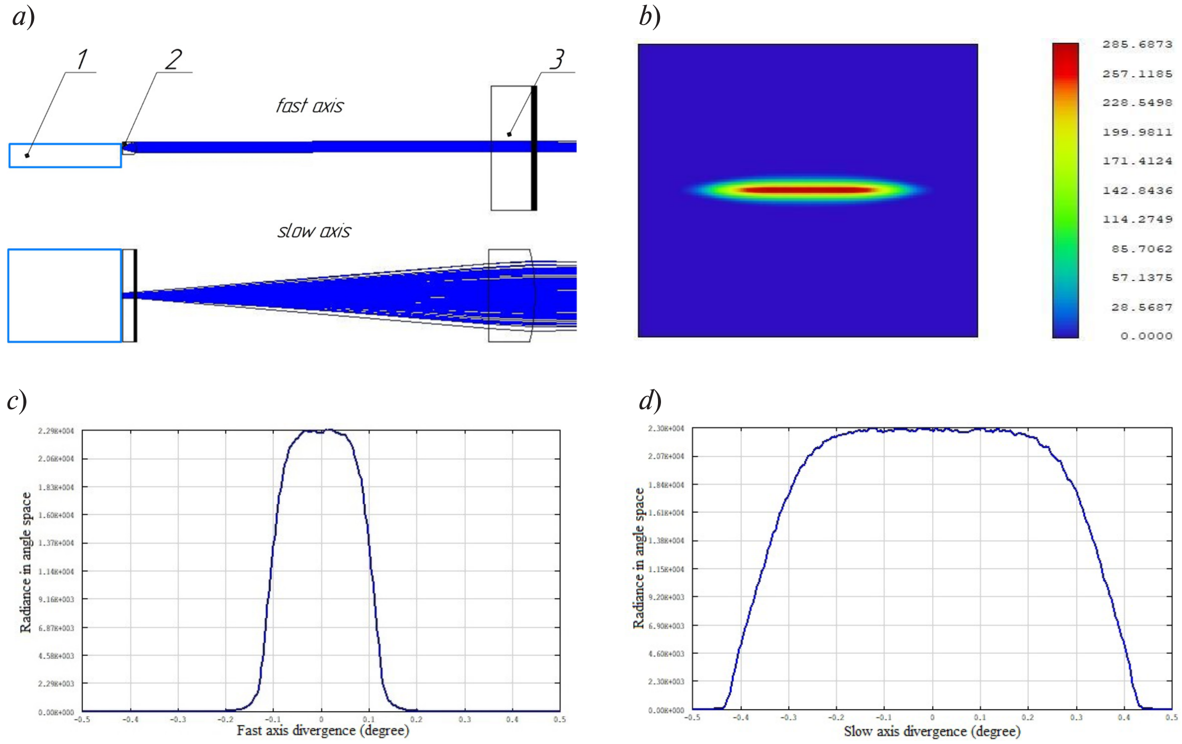

Fig. 2. Fast and slow axis collimation of single-emitter laser diode (*a*): LD *1*; FAC lens *2*, SAC lens *3*; the beam profile after FAC and SAC lenses (*b*), output divergence just after fast-axis (*c*) and slow-axis (*d*) collimation

Table 2 demonstrates the parameters of the single-emitter LD after the collimation.

Table 2

Single emitter parameters after the collimation

Beam parameter	Fast axis	Slow axis
Beam width, mm	0.31	2.5
Divergence half-angle, °	0.127	0.42

The spatial combining of beams includes the LD beams reflection by the mirrors and their alignment above each other in the vertical plane. During the polarization combining of two arrays radiation, the power increases approximately twice without any changes in the geometry parameters of the beam. The combined beam sizes after the PBS are 5.9 mm and 2.6 mm along the fast and slow axes, respectively.

The search for optimal overall parameters of focusing lenses was performed in order to provide efficient coupling of the beam into the fiber. The maximum radiation power in the fiber and the correspondence of the waist dimensions and the beam divergence to the fiber parameters were taken into account when selecting the focal length. The computational simulation results showed the optimal focal lengths of 20 mm for the fast axis and of 9.3 mm for the slow one. The lenses being used, the laser radiation completely couples with 200 μm/NA 0.22 fiber. Table 3 presents the parameters of the focusing spot in the waist plane.

Table 3

Beam parameters of focusing spot

Beam parameter	Fast axis	Slow axis
Beam width, μm	104	130
Divergence half-angle, °	8.6	8.1

Fig. 3 demonstrates the computational simulation results.

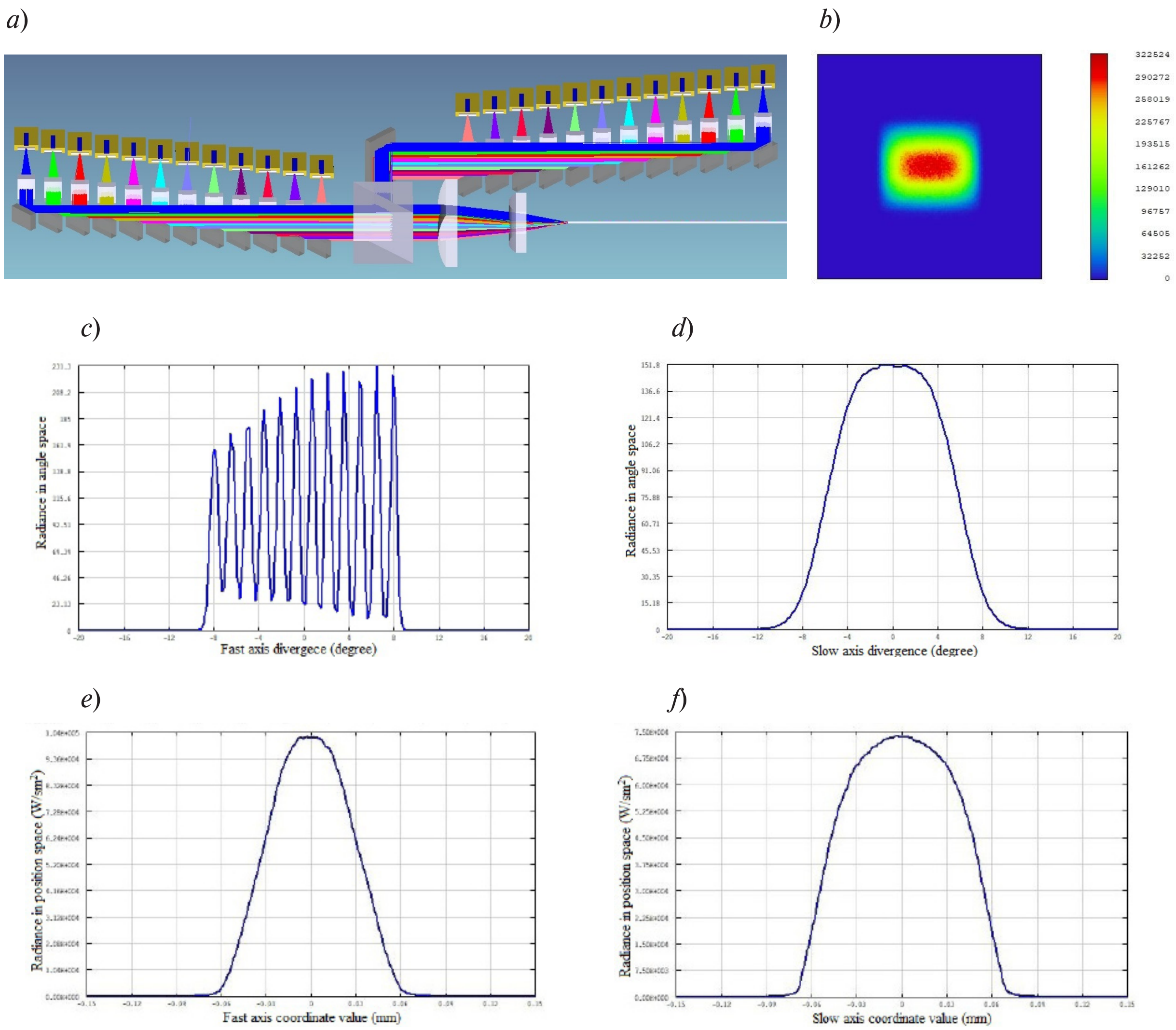

Fig. 3. 3D model of the optical system with ray tracing (*a*), the beam profile of focusing spot (*b*), output divergence just after fast-axis (*c*) and slow-axis (*d*) focusing, radiance distribution of focusing spot for the fast (*e*) and slow (*f*) axis

Conclusion

The simulated results show that the beam fully couples with the fiber in terms of the size and divergence. The coupling efficiency is 89% considering the Fresnel loss, and the losses on the mirrors and the polarized beam splitter. The given optical system was designed as a laser module prototype coupled with the fiber 200/225 μm with a numerical aperture of 0.22, the coupling efficiency being of 83%. The CW output power of the module reached 368 W with the brightness of 7.7 $MW/cm^2 \cdot sr$ in the continuous operation mode.

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