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Fiber laser module with brightness exceeding 10 MW/(cm^2·sr)

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The work was dedicated to the laser modules for the spectral range of 975 nm based on single laser diodes with fiber output to be designed and manufactured. The installation of an optical system for the seven laser diodes radiation input into a silica-silica fiber with a core diameter of 105 μm and a numerical aperture of 0.15 has been carried out while investigating their power and spectral characteristics. The maximum output power of the laser module was 65 W in CW operation at a nominal current of 12 A and a thermal stabilization temperature of 25°C, the total efficiency of the laser module was 43%, and the brightness of the laser module amounted to 10.6 MW/(cm^2·sr).

Keywords: laser module, optical system, laser diodes, fiber lasers.

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Introduction

Laser modules (LMs) with fiber output based on individual laser diodes (LDs) are traditionally used as sources of pumping radiation for high-power fiber lasers [1–3]. The rising market of fiber lasers requires constant enhancement of LM parameters. The most important of these are the radiation power, brightness, total efficiency, width of the radiation spectrum, and service life. The techniques of spatial, polarization, and spectral combining of LD radiation are used to increase the LM output power [4]. Spatial and composite (spatial–polarization) radiation combining techniques are the most widely used ones.

The following are of note among the commercially available devices with spatial LD radiation combining: LMs produced by IPGPhotonics (United States) with the radiation of six LDs introduced into an optical fiber with an aperture of 0.13 [5] and BWTBejing (China) LMs with the radiation of seven LDs introduced into an optical fiber with an aperture of 0.22 [6]. Since an additional increase in the pumping power in multi-kilowatt fiber laser systems may be achieved by combining the radiation of several LMs with the use of intermediate fiber couplers, the use of an output fiber with a lower numerical aperture in LMs is crucial for certain applications. In the present study, the results of development of an LM with spatial combining of the radiation of seven LDs and its subsequent introduction into a quartz fiber with a core diameter of 105 μm and a numerical aperture of 0.15 are reported.

1. Optical LM layout

The optical layout with spatial combining of the radiation of individual LDs, which are shifted vertically relative to each other, and subsequent focusing of the combined beam onto the receiving fiber end was used in the LM design (Fig. 1).

The characteristics of LDs used in the LM are listed in Table 1.

Owing to the significant differences in angular divergence of LD radiation in two mutually perpendicular directions, a separate lens is needed to compensate for divergence

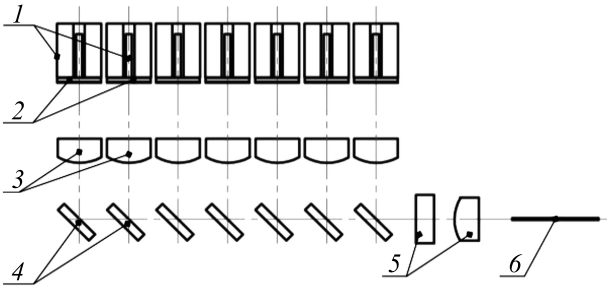

Figure 1. Optical LM layout: *1* — LD, *2* — aspherical microlenses, *3* — cylindrical lenses, *4* — rotary mirrors, *5* — focusing lenses, *6* — optical fiber.

Table 1. LD characteristics

Parameter	Value
Wavelength, nm	975
Emitter width, μm	90
Radiation divergence along the slow axis (95% power inclusion) (I = 12 A, T = 25°C), deg	5.25
Radiation divergence along the fast axis (95% power inclusion) (I = 12 A, T = 25°C), deg	29
Laser radiation power (I = 12 A), W	12

Table 2. Parameters of LD radiation after rotary mirrors (95% power inclusion)

Parameter	Designation	Value
Radiation divergence along the fast axis (92% power inclusion), deg	θ_{fa}	0.13
Radiation divergence along the slow axis, deg	θ_{sa}	0.37
Beam width along the fast axis, mm	ω_{fa}	0.33
Beam width along the slow axis, mm	ω_{sa}	1.3

in each plane. Aspherical D-shaped microlenses with a focal distance of ~ 0.32 mm were used to compensate for divergence of LD radiation along the fast axis (in plane perpendicular to the $p{-}n$ junction). According to datasheet specifications, these lenses ensure propagation of no less than 92% of the LD power within an angle of $\pm 0.13^\circ$. Cylindrical lenses with a focal distance of 7 mm were used to compensate for radiation divergence along the slow axis (in plane parallel to the $p{-}n$ junction). A common parallel beam was formed after reflection off rotary mirrors installed at different elevations. The calculated parameters of radiation after reflection off rotary mirrors are listed in Table 2.

The following expression is used to determine the maximum number of LDs for highly efficient introduction of their radiation into a fiber [7]:

$$N = \frac{D_f \theta_f}{2 D_{fa,sa} \theta_{fa,sa}} \gamma_{fa,sa}, \tag{1}$$

where D_f is the fiber diameter, θ_f is the numerical aperture of the fiber, $D_{fa,sa}$ is the laser beam waist diameter along fast and slow axes, $\theta_{fa,sa}$ is the radiation divergence along fast and slow axes, and $\gamma_{fa,sa}$ is the fill factor.

Inserting the data from Table 2 into Eq. (1), we find that the chosen optical LM layout provides for efficient introduction of radiation of several LDs only if their radiation is combined along the fast axis. It is evident that the LM radiation power may be maximized by minimizing the vertical pitch of LDs. The limiting factor here is the possible „clipping" of radiation of neighboring LDs by rotary mirrors, which is taken into account by fill factor γ_{fa} (this factor is always smaller than unity). Since errors in mounting of D-shaped microlenses always lead to an increase in divergence of laser radiation and to a deviation of the propagation direction of laser beams from the horizontal, the elevation difference of neighboring LDs was set to $450\,\mu$m in the considered LM.

The following conditions were taken into account in choosing the optical elements for focusing the laser radiation onto the receiving fiber end:

$$D_{fa,sa} \le \frac{D_f}{\sqrt{2}},$$

$$\theta_{fa,sa} \le \frac{\theta_f}{\sqrt{2}},$$

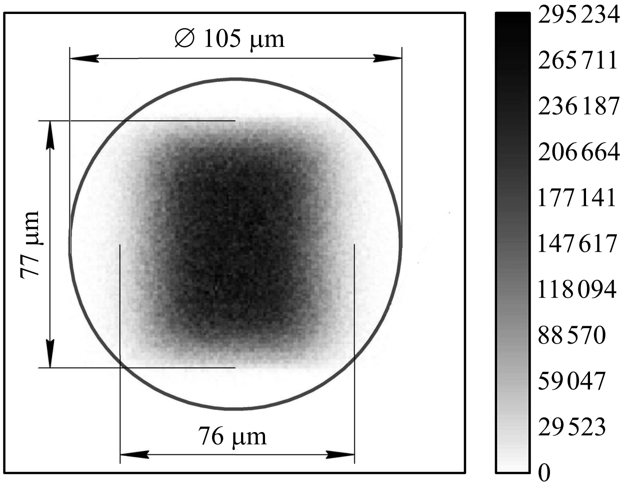

Figure 2. Distribution of laser radiation intensity on the receiving fiber end.

where $D_{fa,sa}$ is the size of the focused beam along fast and slow axes and $\theta_{fa,sa}$ is the angle of propagation of focused radiation along fast and slow axes. Denominator $\sqrt{2}$ accounts for the shape mismatch between the focused beam (square) and the fiber cross section (circle). Two cylindrical lenses for focusing along fast and slow axes were used to focus radiation onto the receiving fiber end in order to compensate for the astigmatism of LD radiation after reflection off rotary mirrors. The results of numerical simulation (performed using the Zemax optical design software) of the distribution of laser radiation intensity on the receiving fiber end are presented in Fig. 2. An antireflective coating was deposited additionally onto the fiber end to reduce losses in the process of introduction of laser radiation into the fiber.

2. Experimental results

The fabricated LM was mounted in a case $14.5 \times 28 \times 78$ mm in size. The optical fiber mount was made in the form of a pedestal with a through hole that was a part of the heat-conducting case. All optical elements of the LM were secured with a special UV-curable glue with linear shrinkage below 0.2%. Figure 3 presents the mutual orientation of LD beams after propagation through lenses installed to compensate for the radiation divergence along fast and slow axes. The maximum radiation divergence along the fast axis did not exceed 0.14° for all LDs, and the maximum mutual horizontal deviation of laser beams was within $\pm 0.11^\circ$. The radiation power of all LDs was measured before and after the installation of rotary mirrors. The loss of power at these mirrors was 5%.

To measure the power and spectral characteristics, the fabricated LM was mounted on a water-cooled base connected to a cooling system with a set water temperature of 25°C. The watt–ampere characteristic was measured with

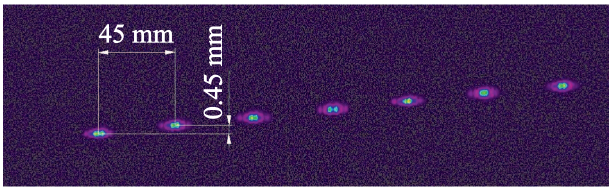

Figure 3. Mutual arrangement of laser beams after propagation through lenses installed to compensate for the radiation divergence along fast and slow axes.

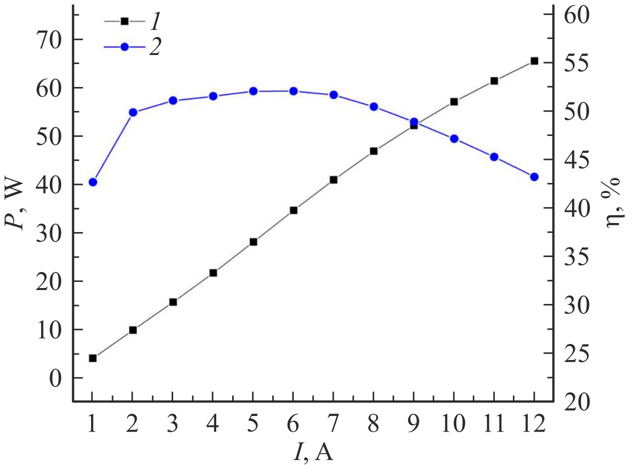

Figure 4. Dependence of the LM output power (*1*) and the total efficiency (*2*) on the pumping current.

a step of 1 A up to a nominal pumping current of 12 A. The watt–ampere characteristic of one of the fabricated LMs is presented in Fig. 4.

The maximum LM output power was 65.4 W at a pumping current of 12 A. This corresponds to a brightness of 10.6 MW/(cm^2·sr) and a total efficiency of 43%. The total efficiency for a pumping current of 6 A was 52%. It is worth noting that the LM efficiency variation is governed by the dependence of the LD efficiency on the pumping current, which is typical of high-power LDs [8,9]. The total LD radiation power losses were 23%. Losses at elements of the optical system accounted for $\sim$ 9%, and the remaining part of losses was due to the efficiency of introduction of the formed laser beam into the optical fiber.

The results of fabrication of a series of LMs were illustrative of high reproducibility of watt–ampere characteristics; the maximum output power was (65 ± 1) W at a nominal pumping current of (12 ± 0.1) A.

The center wavelength of the fabricated LMs was 976–978 nm. The shift of the center wavelength with current did not exceed 1.1 nm/A (Fig. 5). The corresponding value for the LDs used was 1 nm/A.

The LM fabrication process involves hours-long endurance tests during which the power and spectral LM characteristics are measured [10,11]. The duration of endurance tests for the LMs examined in the present study

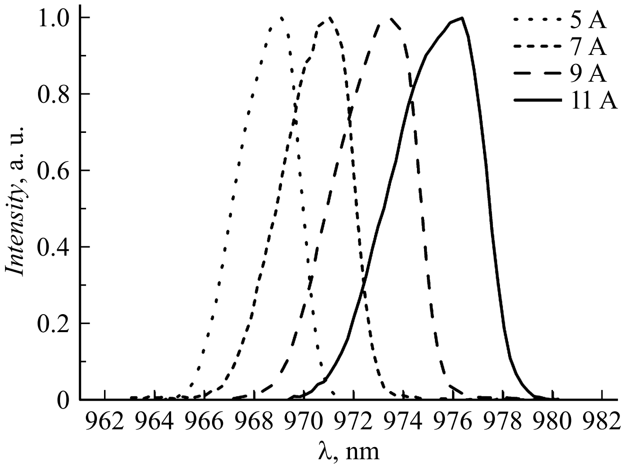

Figure 5. Shift of the LM spectrum envelope with pumping current.

was 40 h in nominal operation conditions. The degradation of radiation power of modules did not exceed 1.1%. This attests to the reliability of the fabricated LMs.

Conclusion

LMs with spatial combining of radiation of seven LDs with an optical system efficiency in excess of 77% [12] were designed and fabricated. The LM output power was 65 W at a nominal current of 12 A. This corresponds to a brightness of 10.6 MW/(cm^2·sr) in the conditions of our experiment with an optical fiber with a core diameter of 105 μm and a numerical aperture of 0.15. The reliability of LMs was verified in endurance tests. It should be noted that these LMs are on par in terms of operating parameters with similar devices produced around the world and are superior to most of them in brightness. The LM radiation power may be increased further by implementing designs with polarization combining of LD radiation.

Conflict of interest

The authors declare that they have no conflict of interest.

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