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Laser diode module over 350 W power output with 200 μm/NA 0.22 fiber

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Abstract: The paper reports the development of the 915 nm laser module (LM) based on high-power single-emitter InGaAs/AlGaAs laser diodes (LDs). The main options to increase the output LM power as compared to the previous sample were considered. The optical system was designed for coupling the beams into a silica-silica fiber with a core of 200 μm in diameter and a numerical aperture of 0.22. The maximum reached CW output power was 368 W at a nominal current of 22 A and thermal stabilization temperature of 20 °C, the total LM efficiency of 47%.

Keywords: laser module, high-power laser diodes, optical fiber

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Материалы конференции
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Лазерный диодный модуль с волоконным выводом излучения мощностью более 350 Вт в 200 мкм волокне с числовой апертурой 0.22

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Аннотация. В работе представлены результаты разработки лазерного модуля спектрального диапазона 915 нм на основе мощных одиночных InGaAs/AlGaAs лазерных диодов. Рассмотрены основные пути увеличения выходной мощности ЛМ по сравнению с ранее представленным образцом. Выходная мощность лазерного модуля составила 368 Вт.

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Introduction

As compared to other laser radiation sources the key advantages of high-power laser diodes (LD) are high power, high reliability, and small size [1]. These products based on such LDs include fiber-coupled laser modules (LM). LMs can be used for pumping high-power fiber lasers. Recently, the intense development of laser technologies requires to continuously increase the output power of pumping modules to produce high-power fiber lasers; for this purpose, various LM designs are offered for combining beams from the maximum possible number of LDs involving spatial, polarization, and spectral beam combining [2]. The objective of the present work is to develop and manufacture a high-power 915 nm LM (not less than 350 W) with output silica-silica 200μm/NA 0.22 fiber.

Materials and methods

In [3], an LM is reported with spatial combining of beams from 6 LDs mounted at different heights in the direction of fast axis. The output power for 105 μm core/NA 0.15 optical fiber was 43.6 W at operating current of 10 A. 975 nm LDs with emitter width of 94 μm and maximum radiation power of 12 W were used as power sources.

Since the LDs have a good polarization purity (>90%), polarization combining of beams from two symmetrical LD arrays with mutually perpendicular polarization is an efficient and cost-effective technique which is relatively easy in implementation to further increase LM output power [4]. The polarization plane of an LD array was rotated by 90 ° by passing the laser beam through a half-wave plate; subsequent combining of beams from two LD arrays was performed by passing radiation through the polarized beam splitter (Fig. 1). The LM polarization combining design provides nearly double increase in LM power as compared to the design based exclusively on the spatial combining. In addition, since the absorption peak width for alumina-silicate optical fibers doped by ytterbium ions at 915 nm is several times larger than that at 975 nm [5], the developed LM does not require LD wavelength stabilization and use of the volume Bragg gratings which would result in additional losses of laser radiation power, as it was shown in [3].

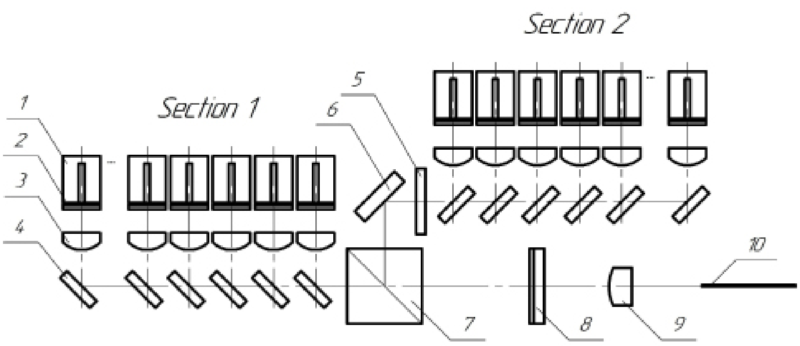

Fig. 1. LM optical design with LD polarization beam combining: LD *1*; acylindrical micro lenses *2*; cylindrical lenses *3*; rotating mirrors *4*, half-wave plate *5*; mirror *6*; polarized beam splitter (PBS) *7*; focusing lenses *8*, *9*; optical fiber *10*

The obvious option to increase LM power is to use higher-power LDs that have been commercially available in recent years. In particular, the LDs simultaneously satisfying the requirements to high power and reliability include LDs with increased emitter width providing the maximum radiation power of 21 W at operating current of 22 A (Table 1).

According to Table 1, the LD emitter width is 190 μm that is two times larger than that of the previously used LDs. High efficiency of laser radiation coupling into the optical fiber is determined by the conditions [6]:

$$N_{FA} \cdot d_{FA} \cdot \theta_{FA} \leq d_{fib} \cdot NA, \quad (1)$$

$$N_{SA} \cdot d_{SA} \cdot \theta_{SA} \le d_{fib} \cdot NA, \qquad (2)$$

where N_{FA}, N_{SA} are the numbers of LDs aligned in series in the direction of the fast and slow axes, respectively; d_{FA}, d_{SA} are the LD emitter widths along the fast and slow axes; $\theta_{FA,}$ θ_{SA} are the beam divergences along the fast and slow axes; d_{fib} is the optical fiber core diameter; and NA is the fiber numerical aperture.

Eq. (2) shows that in case of twice increased LD emitter width laser radiation can be efficiently coupled into the fiber along the slow axis only with the appropriately increased fiber core diameter or fiber NA. For this purpose, 200 μm/NA 0.22 fiber was used in the developed LM. Note that the optical fiber with the given parameters allows not only efficient coupling of laser radiation along the slow axis but also significantly increasing the number of LDs aligned in series in the direction of the fast axis. The required LM power was provided by the design with combining of beams from 24 LDs and with spatial combining of beams from 12 LDs mounted at different heights along the fast axis.

Table 1

LD parameters

Parameter	Value
Maximum operating current, A	22
Maximum output power, W (I=22 A)	21
Emitter width, μm	190
Efficiency, %	60
Center wavelength, nm	915±10
Wavelenght shift versus temperature, nm/°C	0.3
Beam divergence (FWHM) along the fast axis, °	29
Beam divergence (FWHM) along the slow axis, °	9

The advantage of using higher-power LDs in the LM design is keeping the minimal size of the developed product. However, keeping the high density of LD packing results in the problem of increasing the efficiency of heat removal from LD since insufficient heat removal can considerably constrain the growth of LM power during operation at maximal or near-maximal operating currents and affect the LM efficiency. The LDs used in the work were soldered to the heat-conducting ceramic substrate using AuSn solder, the substrate was soldered to the copper heat sink using indium solder. In [3], indium foil gaskets were used as a thermal interface material to provide the minimum thermal resistance between surfaces of the enclosure and heat sink with the mounted LDs. In the present work, the following heat-conducting materials were considered when assembling a new LM experimental design: indium foil gaskets with thermal conductivity of 80–90 W/m·K, graphite sheet with thermal conductivity of 700 W/m·K, and thermal paste with thermal conductivity of 0.65-1 W/m·K. Due to its low thermal conductivity, the thermal paste was applied as a thin layer filling the microroughnesses on the heat-exchanging surfaces. Heat removal efficiency was estimated based on the watt-ampere characteristic measurements and dependency of wavelength on operating current at the heat sinks with 6 mounted LDs. During measurements heat sinks were mounted on the copper water-cooled base with thermal stabilization temperature of 20 °C, connected to the water cooling system with flow rate of 7 l/min. Watt-ampere characteristic measurements and dependencies of wavelength on operating current for different thermal interfaces are presented in Fig. 2. For graphite sheet used as a thermal interface material the maximum laser radiation power of 126 W at operating current of 22 A was achieved. For thermal paste and indium foil in similar modes radiation power was 125.2 W and 123.2 W, respectively. The maximal LD radiation wavelengths for graphite sheet and indium foil were 918.4 and 919.7, respectively, which corresponds to the operating temperature difference of ~ 4.3 °C in the LD active area.

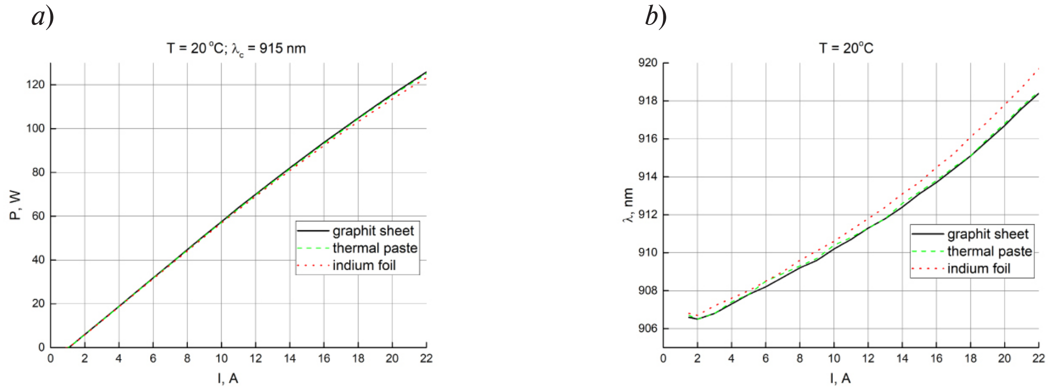

Fig. 2. Characteristics of the heat sink with 6 mounted LDs: watt-ampere characteristic (*a*); LD radiation spectrum versus operating current (*b*)

Although no significant difference in laser beam characteristics for graphite sheet and thermal paste was revealed, the use of graphite sheet is more preferable since thermal paste coating of reproducible thickness is a technologically difficult process; besides, thermal paste characteristics can degrade with time.

The loss of LM laser radiation power is mainly caused by the losses on the elements of the optical system the total efficiency of which can be determined by the expression:

$$\eta_{opt} = \eta_{fr} \cdot \eta_{mirr} \cdot \eta_{pol} \cdot \eta_{coupl}, \quad (3)$$

where η_{opt} is the total efficiency of the optical system; η_{fr} is the coefficient taking into account the reflection loss from the surfaces of the optical elements; η_{mirr} is the coefficient taking into account 'clipping' loss at the rotating mirrors; η_{pol} is the polarization combining efficiency; and η_{coupl} is the efficiency of laser radiation coupling into the fiber. The results of the loss assessment are presented in the following section.

Results and discussion

An additional antireflective coating was deposited onto the fiber's facet to reduce losses in the process of introduction of laser radiation into the fiber. To determine coefficient η_{fr}, technical characteristics of the optical elements used in the design were considered, i.e. reflection coefficients for the reflecting elements and antireflection coating coefficients for the transmissive optics; the value of coefficient η_{fr} was 0.98. The coefficient η_{pol} was determined experimentally by measuring radiation power from both LD arrays before and after the PBS; the value of coefficient η_{pol} was 0.95. To determine the loss coefficient η_{mirr}, LD radiation power was measured before and after the rotating mirrors were mounted; the value of coefficient η_{mirr} was 0.97. To determine coefficient η_{coupl}, LM watt-ampere characteristic was measured (Fig. 3 *a*), and the coefficient was calculated as a ratio of radiation power at the optical fiber input to the output power; the value of coefficient η_{coupl} was 0.92. The loss at radiation coupling into the fiber could be conditioned by the errors in mounting the optical elements (installation inaccuracy, additional shifting during glue polymerization); the current work has not considered the individual influence of these parameters. The total efficiency of the optical system η_{opt} was 0.83. During the measurements the absence of beams from three LDs was noted that was, probably, due to their failure at the stage of mounting the focusing optics elements. When measuring the optical losses the initial power values for these LDs were not considered.

The maximum reached CW output power of LM was 368 W at nominal current of 22 A and thermal stabilization temperature of 20 °C, the total LM efficiency being of 47%. LM spectral characteristics are shown in (Fig. 3,*b*). The center wavelength at the maximum current was 923.8 nm, the spectrum width was 6 nm, the shift of wavelength versus current was ~ 0.7 nm/A that agrees with the similar values for laser modules of such type. At that, the predicted resulting maximum LM radiation power could achieve a value of 420 W providing that all the LDs operated properly.

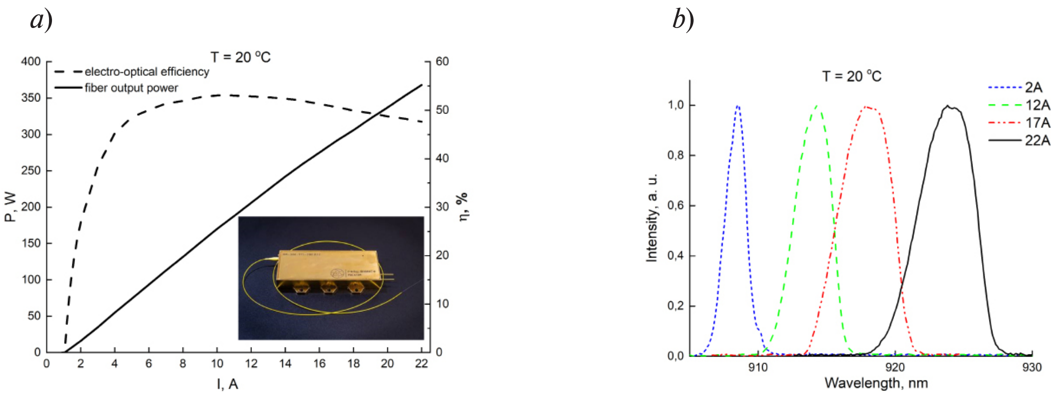

Fig. 3. LM optical power and electro-optical efficiency versus drive current (*a*), radiation spectrum versus operating current (*b*)

Conclusion

The paper reports the development of the high-power 915 nm laser module based on the spatial and polarization combining of beams from high-power single-emitter InGaAs/AlGaAs LDs. The main options to obtain the maximum LM efficiency were considered which made it possible to significantly increase the output LM power as compared to the previously reported sample.

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