A temperature effect study on the laser diode module spectral characteristics

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Abstract. The paper presents the study results of the semiconductor laser active medium temperature effect, that changes in time during its operation, on its output spectral characteristics. Experimental dependences of the diode laser emission spectra on the laser crystal temperature in the range from 296 to 320 K are investigated. Using a heat fluxes computer model the possible reasons were analyzed for the time variation of the laser diode module spectral characteristics with several single emitters that are fixed on the ladder platform. The obtained results can be used for the large-scale laser diode modules design, including a large number of emitters, with high requirements for the output characteristics stability. Thermal fields and isothermal surfaces for a laser diode module with total thermal loads exceeding 30 W are studied.

1. Introduction

Semiconductor lasers, including high-power semiconductor lasers, have been in great demand in recent decades in a wide range of areas of their practical application: optical pumping sources for solid-state and fiber lasers, gas analyzers, medical and industrial applications, additive technologies, metrology, printing, robotics. Such popularity is associated with high values of efficiency, compactness, reliability and a high level development of manufacturing technology for both single emitters and bars, modules and laser diode assemblies [1].

One of the important parameters determining the scope of their application is the output spectral characteristics. Laser diodes are very sensitive to temperature changes that have a significant effect on their emission spectra [2]. It is precisely the high sensitivity to heating that is one of the barriers to the further development of the technology for creating laser diode modules from a large number of emitters. In such devices lasers are fixed on the metal complex step configuration bases – each subsequent single emitter is located on a step, the height of which exceeds the height of the previous one. This is a determining factor in the difference in the heat removal conditions and the single laser diodes heat fluxes propagation, which affects the temperature difference between their active medium and as a result their output spectral characteristics. The difference in the semiconductor lasers emission spectra that make up a single module may cause the entire module emission spectrum to broaden and redshift during operation, which negatively affects the large-scale semiconductor laser modules practical application. An urgent task is to ensure the spectral maximum position stability and the spectra width at half-height during the high-power laser modules operation [3].

The research objective is experimentally determining the semiconductor lasers spectral characteristics temperature dependence to create a laser diode module computer model and analyze the
effect of conditions differences of single emitters heat removal that make up the module due to the difference in the steps height of the mounting base on its output spectral characteristics.

2. Numerical solution of a thermal problem
In order to visualize the temperature profiles arising in the laser diodes working process, and to analyze the effect of the heat sink system on the module thermal mode, it is necessary to build the device thermal model at the design stage. The thermal problem numerical computation for the created spatial model is performed using the Comsol Multiphysics 5.3 software.

2.1. Problem formulation
In the developed laser diode module thermal model, the following basic parameters of all structural elements are taken into account: density, specific heat capacity, thermal conductivity, coefficients of thermal expansion along three spatial axes and geometric dimensions. The general thermal model of the radiator includes a semiconductor crystal, metal contacts (on both sides of the base), and a thermally conductive ceramic base. Due to the laser heterostructure layers have a scale significantly smaller than the scale of other structural laser module elements, to accelerate the calculations the laser crystal is considered completely made of GaAs and experiencing a thermal load (heat flux) equal to the load on the heat-conducting layers of the real layered laser structure (calculated as the ratio of a single emitter heat dissipation maximum power to the stripe contact area). Ambient conditions are taken close to the ambient conditions in the laboratory, in which preliminary measurements and the laser diode module assembly were made.

To reduce the calculation time, and also due to the direct lack of need for component-based modeling of a thermoelectric cooler, to take into account the active cooling system influence as a boundary condition applied to the laser diode module base face, a fixed temperature equal to 293 K was chosen close to room temperature and above the dew point for the specified humidity value in the room. The resource mode simulation of operation below the dew point was not made, since the semiconductor lasers operation in this mode requires special cells [4]. The device is considered to be placed in a sphere with a radius of 3 meters, filled with air, that allows to take into account the contribution of natural convection to heat exchange processes. The created model does not take into account the influence of mechanical and thermal stresses arising due to differences in materials thermal expansion coefficients and thermal loads.

2.2. Measuring bench model
Initially the thermal problem numerical solution was carried out for a measuring bench computer model including a laser diode operating in the maximum heat generation mode, an assembly base, and a platform for mounting spring contacts. The mounting base has an opening for fixing the thermal sensor that ensures the automated operation of the thermoelectric element used as a cooler. The simulation results for the emitter with 10 W heat dissipation power are shown in figure 1.

The maximum temperature is observed in the center of the stripe contact (about 320 K). This value is within the resource thermal mode of the emitters used (the temperature of the active region should not exceed 333 K), the overheat value relative to the base face of the mounting substrate is 27 K, and relative to the upper face is 21 K.
Figure 1. The simulation results for the emitter with 10 W heat dissipation power.

The analysis of the plotted isothermal surfaces (figure 2) shows their high homogeneity that can be caused by the parallelism of the stripe contact of the laser and the mounting substrate base face, as well as the reliable thermal contact provision under the established boundary conditions.

Insignificant heat fluxes heterogeneity (shown by arrows) may be a laser diode crystal asymmetric arrangement consequence relative to the center of the submount, as well as the laser diode itself relative to the mounting substrate working face center, that causes differences in the various radiator faces thermal conditions and its active area. An additional contribution to the heterogeneity of heat flux makes an opening for the sensor.

Figure 2. Measuring bench computer model isothermal surfaces and heat fluxes.

2.3. Laser diode module model
A laser diode module thermal model includes five emitters with a total heat output of 60 W placed on a heat sink base in a metal packing. All assumptions and boundary conditions described earlier in the paper were taken into account. The difference in height of the individual laser diodes is 1.6 mm. Thus, the height difference between the lowest and highest emitters is 6.4 mm. The temperature of the module packing base surface is fixed (293 K).

Figure 3 presents the results of the thermal problem numerical solution for a module continuous operation period of 3000 seconds. During the solution, it was established that each of the emitters temperature is within the laser crystal operation thermal resource mode. The laser diode temperature at the highest step is 321 K, at the lowest step is 317 K. Thus, according to the model, the emitters total temperature difference in the module does not exceed 4 K. This value is not critical for a module that includes a small number of laser diodes, however, in larger systems the temperature difference will be much higher.
3. Experimental results
The temperature dependence study of the laser diodes output spectral characteristics is performed using measuring bench with precise IR-spectrometer. The bench design includes: a laser emitter, a mounting substrate, a thermoelectric element, a metal heat-conducting base, a thermoelectric element controller, an optical system, an optical fiber, a spectrometer. The optical system provides fiber coupling using the free space method. A controller with a built-in thermal sensor provides automated stabilization of the mounting substrate base face temperature. The laser emitter submount temperature is recorded using thermocouples. When studying changes in the laser diode output spectral characteristics in time measurements are made while ensuring the constancy of the mounting substrate base face temperature (293 K). The temperature dependence study of the emitter output spectral characteristics is performed using a thermoelectric element in the heater mode, that allows for a gradual controlled increase in the submount temperature, and hence the laser active region.

Figure 5 presents the results of the laser diode studying the emission spectra as a function of the laser heterostructure temperature. The laser crystal temperature is determined by the computer model.
using the mounting base upper surface temperate measuring results. The upper surface temperature gradually increased from 296 to 308 K, that corresponds, according to the computer model, to a change in the laser crystal temperature from 296 to 320 K. With increasing temperature an increase in the spectral maximum wavelength occurs with an emission spectra redshift. The average temperature spectral shift is 0.35 nm/K. Therefore, the laser diodes spectral maximum shift that make up the laser module under study will be about 1.4 nm. With an increasing in the module scale and the emitters number, the spectral shift may increase to 3-5 nm, that may adversely affect the possibility of using a powerful laser diode module in devices with increased requirements for spectral characteristics.

![Figure 5. Emission spectra of a laser diode as a function of the temperature of the mounting base upper surface.](image)

4. Conclusion

The developed computer model for the laser diode module thermal problem numerical solution makes it possible to estimate the device components temperatures during its continuous operation for a sufficiently long time. Using of stepped configuration mounting bases as a laser diode modules basic heat-removing elements affects the occurrence of differences in the emitters heat transfer conditions, which leads to additional heating of laser diodes at higher steps, shifting their spectral maximums. Such a shift is insignificant for small modules, however, it can lead to a significant change in the high power devices emission spectra as a result of their heating during operation. To increase such modules output characteristics stability requires a special approach to the heat sink system design.

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