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Predicting the Service Life of High-Power Laser Diodes, Based on Their Radiation Spectrum at the Initial Stage of Operation

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Abstract—A way of predicting the service life of high-power wide-contact laser diodes is proposed, based on spectral measurements at the initial stage of operation of these devices. The forming of spectra and channels of generation in these devices with different pumping and service lives is considered.

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INTRODUCTION

Powerful semiconductor laser diodes (LDs) with quantum-sized heterostructures are widely used in different fields of science, technology, and medicine. LDs with continuous wave generation from several hundred milliwatts to 20 W (the maximum value of power reached at the present time) are usually considered such lasers [1–5]. Studies show that the service life of LDs with power efficiencies of 0.5 to 2 W does not exceed 5000 hours [6]. Several ways of predicting the service life of powerful LDs are known [1, 5, 7], but they are associated with high expenditures of laser resources, the use of costly instrumentation, and discontinuities in the operation of LDs. The problem of predicting the service life of powerful LDs (not only for short periods of time, but in the initial stage of their operation as well) is thus relevant.

EXPERIMENTAL

During testing, we observed the transformation of the emission spectrum of a batch of LDs manufactured in 2012 [7, 8]. It manifests in the transition from three pronounced profiles enveloping the LD emission spectrum and corresponding to three spatial channels of generation in the active region of a LD, to four lines (i.e., to generation in four channels).

We associate the changes in the emission spectrum of the LDs with spatial variations related to the nonlinear refraction coefficient of a quantum well semiconductor and the length of LD radiation coherence. Our calculations showed that fewer channels of generation correspond to a greater coherence of LD radiation, and a reduction in length L_{coh} of coherence raises number N_{chan} of channels [7]:

$$N_{\text{chan}} \approx nW\sqrt{\frac{2\pi}{\lambda L_{\text{coh}}}}, \tag{1}$$

where n is the effective refractive index of the laser waveguide; W is the width of the active region; and λ is the radiation wavelength.

The results from studying the spectral characteristics of an LD batch manufactured in 2017 are presented in this work. They were of the same design as the LDs from the previous batch. Only two channels of generation with central frequencies ν_{01} and ν_{02} were recorded in the first few hours of LD operation. In accordance with (1), we may conclude the length of coherence of the LDs from the new batch of devices was longer than that of the LDs from the previous batch, where there were three profiles.

Three channels of generation $f_{\text{calc}.i}\left(\frac{\nu-\nu_{0i}}{\Delta\nu_i}\right)$, each of which corresponded to a line enveloping the emission spectrum with central frequency $\nu_{01} < \nu_{02} < \nu_{03}$ appeared in the LD spectrum after 240 hours of operation $f_{\text{op}}(\nu)$. An analysis of functions $f_{\text{calc}.i}\left(\frac{\nu-\nu_{0i}}{\Delta\nu_i}\right)$, showed that all three lines were symmetrical with respect to frequencies ν_{01}, ν_{02}, ν_{03} and the condition

$$f_{\text{op}}(\nu) = \sum_{i=1}^{N} f_{\text{calc}.i}\left(\frac{\nu-\nu_{0i}}{\Delta\nu_i}\right), \tag{2}$$

where N is the number of channels of generation, is met in those spectral regions where they are superimposed.

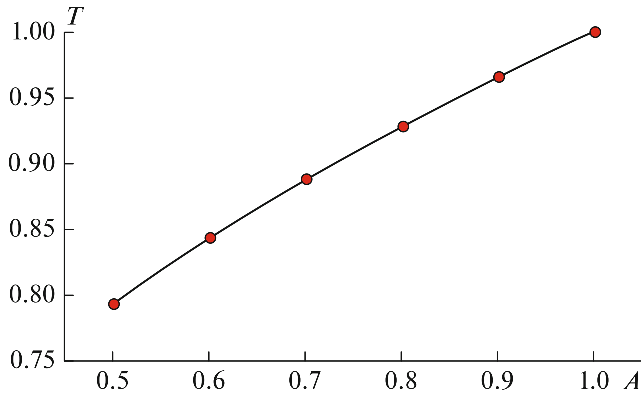

Fig. 1. Dependence of parameter T on the value of parameter A in the initial stage of LD operation.

Four or five channels of generation (Figs. 1a and 1b) appear in the emission spectrum of the LDs after raising their operating time to 350 hours. According to (1), this means a drop in the length of coherence.

Raising the number of channels increases the number of bands in the spectra. This is because the amplification profile is fairly wide (about 6 nm along the wavelength) and must be filled with radiation lines corresponding to different channels.

A technique developed earlier for associating the service life and the value of the parameter A_i [9] in each channel of generation is proposed separately for predicting the service life of a powerful LD.

Functions $f_{\text{calc.}i}\left(\frac{\nu-\nu_{0i}}{\Delta\nu_i}\right)$ were compared to Gaussian function $f_G\left(\frac{\nu-\nu_{0i}}{\Delta\nu_i}\right)$ within the width of the i-th line $\Delta\nu_i$ for a quantitative analysis. Integral spectral parameter A_i was introduced to perform such an analysis within each channel of generation. Its value was calculated using the formula

$$A = 1 - \int_{\nu_{\frac{1}{2}\min}}^{\nu_{\frac{1}{2}\max}} \frac{\left|D\left(\frac{\nu-\nu_0}{\Delta\nu}\right)-1\right| d\nu}{\Delta\nu}, \quad (3)$$

where $\nu_{\frac{1}{2}\min}$ and $\nu_{\frac{1}{2}\max}$ are the frequencies that determined from the condition

$$f_{\text{calc.}i}\left(\nu_{\frac{1}{2}\min}\right) = f_{\text{calc.}i}\left(\nu_{\frac{1}{2}\max}\right) = f_G\left(\nu_{\frac{1}{2}\min}\right) = f_G\left(\nu_{\frac{1}{2}\max}\right) = 0.5, \quad (4)$$

$$D\left(\frac{\nu-\nu_0}{\Delta\nu}\right) = \frac{f_{\text{op}}\left(\frac{\nu-\nu_0}{\Delta\nu}\right)}{f_G\left(\frac{\nu-\nu_0}{\Delta\nu}\right)}, \quad (5)$$

where ν_{0i} is the central frequency of the i-th range of frequencies ν_i, in which Gaussian function $f_G\left(\frac{\nu-\nu_{0i}}{\Delta\nu_i}\right)$ and function $f_{\text{calc.}i}\left(\frac{\nu-\nu_{0i}}{\Delta\nu_i}\right)$ are compared.

The value of frequency ν_{0i} was determined using the formula

$$\nu_0 = \frac{1}{2}\left(\nu_{\frac{1}{2}\max} + \nu_{\frac{1}{2}\min}\right), \quad (6)$$

and the normalized Gaussian function had the form

$$f_G\left(\frac{\nu-\nu_0}{\Delta\nu}\right) = \exp\left[-4\ln 2\left(\frac{\nu-\nu_0}{\Delta\nu}\right)^2\right]. \quad (7)$$

It follows from (3) and (5) that the value of parameter A_i tends to unity when function $f_{\text{calc.}i}\left(\frac{\nu-\nu_{0i}}{\Delta\nu_i}\right)$ can be approximated by a Gaussian function. The way of calculating parameter A_i in different channels of generation is universal. However, the form of function $f_{\text{calc.}i}\left(\frac{\nu-\nu_{0i}}{\Delta\nu_i}\right)$ depends on the pump current. We can see in Fig. 2 that the shape of curve $f_{\text{emp}}\left(\frac{\nu-\nu_0}{\Delta\nu}\right)$ describing the line enveloping the emission spectrum of the LD changes noticeably when the pump current is raised from 940 to 980 mA.

The number of functions $f_{\text{calc.}i}\left(\frac{\nu-\nu_{0i}}{\Delta\nu_i}\right)$; analyzed using formulas (3)–(7) also grows along with the number of channels of generation. However, this does not violate the criterion for predicting the service life of an LD using parameter A.

In predicting the service life of an LD from a batch of mass-produced devices created in one and the same technological cycle, it was found that it can vary from 2500 to 3500 hours. Parameter T was therefore used to determine the quality of each sample of LDs from a particular batch of devices, along with parameter A:

$$T = \frac{\tau}{\tau_{\max}}, \quad (8)$$

where τ is the service life of a specific LD sample from a particular batch of devices in real time; $\tau_{\max}$ is the maximum operating time of an LD from the same batch of devices.

It was also established experimentally (Fig. 1) that parameters T and A when $A > 0.855$ (i.e., during laser diode generation in the fundamental mode) are interconnected by the relation

$$T = A^{1/3}. \quad (9)$$

A feature of these studies is that the lines enveloping the LD emission spectrum with central frequen-

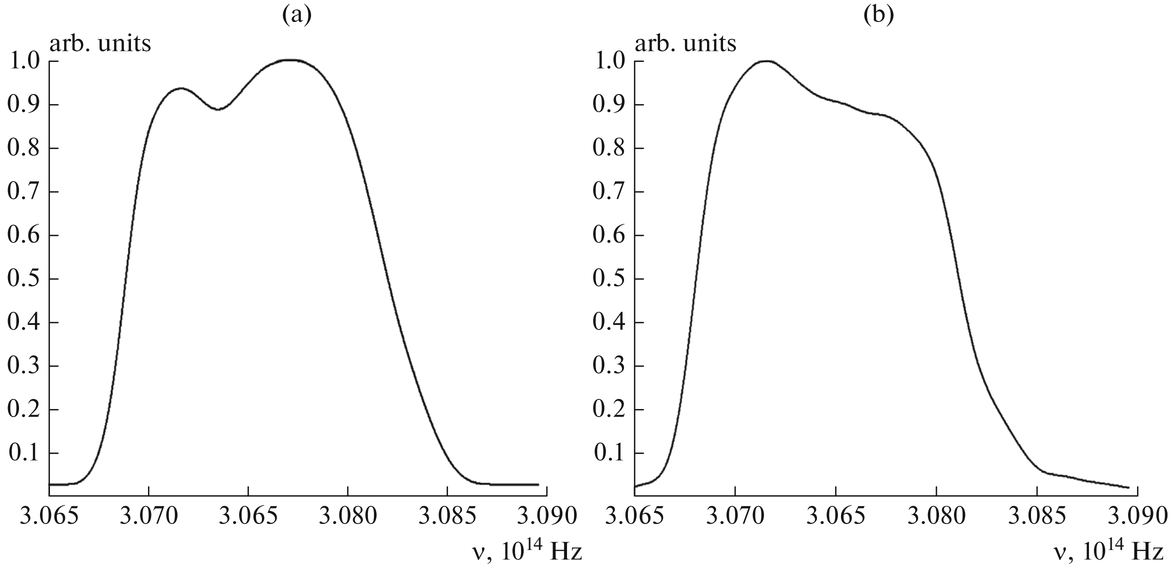

Fig. 2. Envelope line of a normalized LD emission spectrum with an operating time of 350 hours at two characteristic values of the pump current: (a) $I_p = 940$ and (b) $I_p = 980$ mA.

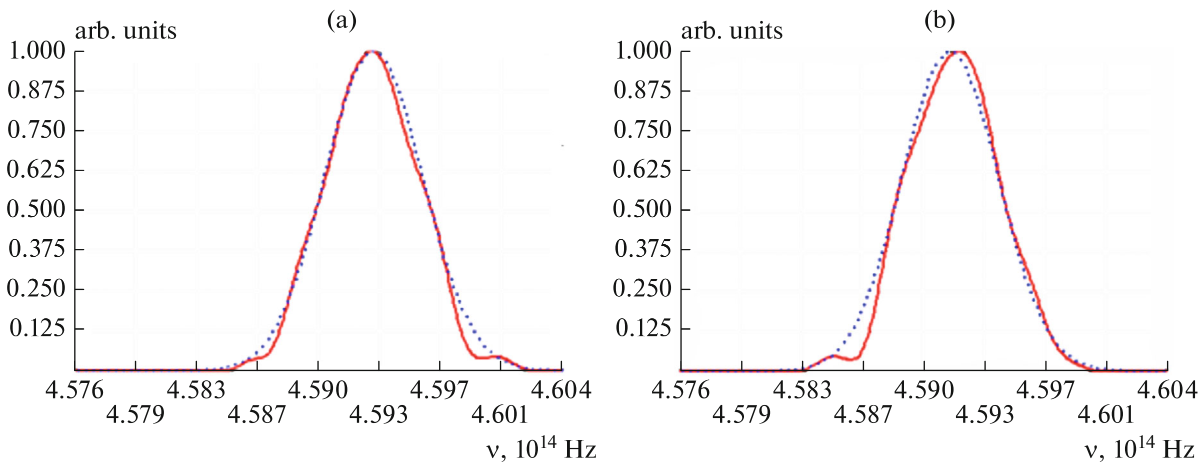

Fig. 3. Profile enveloping the emission spectrum in the first channel of generation of an LDD-10 with a central frequency of 3.072×10^{14} Hz, a width of 0.573×10^{12} Hz, and pump currents of (a) 940 and (b) 980 mA.

cies ν_{0i} were analyzed in a wide range of pump currents (from 940 to 980 mA). The choice of this range was due to the emission spectrum of the LD being largely transformed within its boundaries.

The spectral lines of radiation at two characteristic values of the pump current (940 and 980 mA) are shown in Fig. 2. Four channels of generation are observed at a pump current of 940 mA, and five channels of generation are observed at a pump current of 980 mA. The appearance of the fifth channel of generation means that part of the radiation energy redistributed earlier between the four channels of generation moves into the fifth channel with the highest value, $\nu_{0i=5}$. This explains the transformation of the emission spectrum. A profile with a central frequency of 3.072×10^{14} Hz at LD pump currents of 940 and 980 mA is shown in Fig. 3 as an example of determining coefficient A_i.

An analysis of functions $f_{\text{calc.}i}\left(\dfrac{\nu - \nu_{0i}}{\Delta\nu_i}\right)$ showed they were close to Gaussian, and the values of A_i were in the range from 0.89 to 0.95. According to (9), parameter T in this case varied from 0.962 to 0.983. Since the value of $\tau_{\max}$ in the batch of LDs to which the considered device belongs is 3450 h, we may assume its service life must be close to 3390 h. LDs are now undergoing accelerated tests to determine the real service life of the powerful LDs considered in this work.

CONCLUSIONS

A way of predicting the service life of high-power laser diodes by measuring the emission spectrum in the first hours of their operation was considered. The emission spectrum is a superposition of several emission spectra of individual channels of generation. An analysis of the emission spectrum in each channel of generation allows us to determine the value of parameter A_i characterizing the difference between the profile that envelops the emission spectrum in the channel and the Gaussian distribution. The service life of high-power diode lasers can be predicted from the obtained values of parameter A_i.

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