ISSN 1062-8738, Bulletin of the Russian Academy of Sciences: Physics, 2021, Vol. 85, No. 2, pp. 184–188. © Allerton Press, Inc., 2021.
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Determining the Rate of Degradation of a High-Power Laser Diode from the Dependence of the Radiation Spectrum on Variations in the Pumping Current

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Received August 28, 2020; revised September 25, 2020; accepted October 28, 2020

Abstract—A way is proposed for measuring the rate of degradation of a high-power continuous-wave laser diode with a wide contact by monitoring the state of its heterostructure every 50 h of operation. The number and structure of the channels of laser generation is used as a controlled parameter. The mechanism of the laser diode structure's degradation is considered in the time dependence of the number of lasing channels.

DOI: 10.3103/S1062873821020064

INTRODUCTION

Semiconductor laser diodes (LDs) with quantum-well heterostructures and continuous generation power of several hundred milliwatts to several watts find wide application in different fields of science and technology [1–5]. The most important technical and economic LD parameter is its service life. This is why the development of new ways of monitoring the state of an LD's heterostructure, predicting its service life, and improving such procedures have been of the greatest interest for several decades.

Several ways for monitoring the state of powerful LDs and predicting their service life are known [6–10]. The classical technique, based on measuring the LD radiation power at a constant pumping current, is used most often. The service life is in this case is defined as the time after which the power drops to a certain predetermined level. There is another technique associated with measuring the LD radiation power. The operating time is in this case defined as the time after which it becomes impossible to maintain power at a constant level by increasing the pumping current [11].

A technique based on the radiation pattern's temporal dependence [12] is used much less often to predict the LD service life, and one based on an analysis of the time dependences of the radiation's linear polarization (contrast) [13]. However, these approaches require considerable consumption of the laser resource and the use of statistical ways of processing a large set of data obtained from diagnostics of a batch of devices manufactured in the same technological cycle as those studied in this work.

In mass production, the problem of determining the quality of a single electronic device (particularly active LD elements) is of great importance [14].

DETERMINING THE STATE OF THE HETEROSTRUCTURE OF A POWERFUL LD FROM THE NUMBER OF LASING CHANNELS

Certain steps to solve this problem were taken in [10] while testing a batch of powerful LDs fabricated in a single technological cycle. It was considered that the earlier way of determining the state of an LD heterostructure from its spectral characteristic can only be used if the fundamental mode is generated. Powerful LDs have a complex form of the emission spectrum envelope. We therefore analyzed this spectrum by decomposing it into components in order to determine the state of the LD heterostructure.

At the start of laser testing, the operating time of each device varied from 270 to 310 h. After 40–80 h from the start of testing, line contour $f_{\exp}(\nu)$ enveloping the LD emission spectrum could be represented as a superpositioning of three line contours $f_{\mathrm{cal}.i}\left(\frac{\nu-\nu_{0i}}{\Delta\nu_i}\right)$ with central frequencies $\nu_{01} < \nu_{02} < \nu_{03}$. Each contour corresponded to the spatial lasing channel in the active region of laser diode. Analysis of calculated functions

$f_{\text{cal}.i}\left(\frac{\nu-\nu_{0i}}{\Delta\nu_i}\right)$ showed that only when all three lines were symmetric with respect to the frequencies ν_{01}, ν_{02}, ν_{03} was condition (1) satisfied:

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

where N is the number of lasing channels (in this case, $N = 3$).

A change in the shape of LD spectral line $f_{\exp}(\nu)$ was observed during LD testing due to the number of lasing channels growing from three to four.

We associate such changes in the LD emission spectrum with variations in the coefficient of nonlinear refraction of the semiconductor in a quantum well and the length of radiation coherence in the channels during LD operation. Calculations showed that a smaller number of lasing channels corresponds to a greater degree of LD radiation coherence, and an increase in the number of channels N_{ch} means that length L_{coh} of radiation coherence in the channels is reduced [7]:

$$N_{\text{ch}} = W\sqrt{\frac{2\pi n}{\lambda_0 L_{\text{coh}}}}, \tag{2}$$

where $n = 3.56$ is the effective refractive index of the laser waveguide for the fundamental lateral mode, $W = 100$ μm is the width of the active region, and λ_0 is the wavelength of LD radiation. In this work, we studied an LD with measured value $\lambda_0 = 976$ nm (average frequency, $\nu_0 = 3.075 \times 10^{14}$ Hz).

RESULTS FROM STUDYING THE STRUCTURAL STATE AND RATE OF THE DEGRADATION OF A POWERFUL LD MODEL ATS-S200-100-980

Below, we present the results from investigating the structural state and the rate of degradation of a model ATS-S200-100-980 LD with a LDD-10 driver. This LD with a 100 μm contact had threshold pump current $I_{\text{th}} = 497$ mA and a rated value of radiation power $P = 500$ mW upon doubling the threshold. The spectral characteristics of a new batch of LDs manufactured using the same technology and having the same design as the lasers studied in [10] were used as control parameters. An important factor in this work was that the operating time of all lasers was known precisely and did not exceed 10 h. In the first few hours of our study, all LDs had only two lasing channels with central frequencies ν_{01} and ν_{02}. According to (2), this means that the LD radiation at the initial stage of operation was characterized by a long length of coherence: $L_{\text{coh}} = 5.6$ cm.

After 200–250 h of operation, a third lasing channel appeared in the LD, meaning the length of coherence fell to $L_{\text{coh}} = 2.5$ cm. As was shown in [10], each lasing channel of number i in the emission spectrum corresponded to line profile $f_{\text{cal}.i}\left(\frac{\nu-\nu_{0i}}{\Delta\nu_i}\right)$ with central frequency ν_{0i}. The emergence of the third lasing channel therefore meant that line contour $f_{\exp}(\nu)$ which envelopes the LD emission spectrum was a superpositioning of three line contours with central frequencies $\nu_{01} < \nu_{02} < \nu_{03}$.

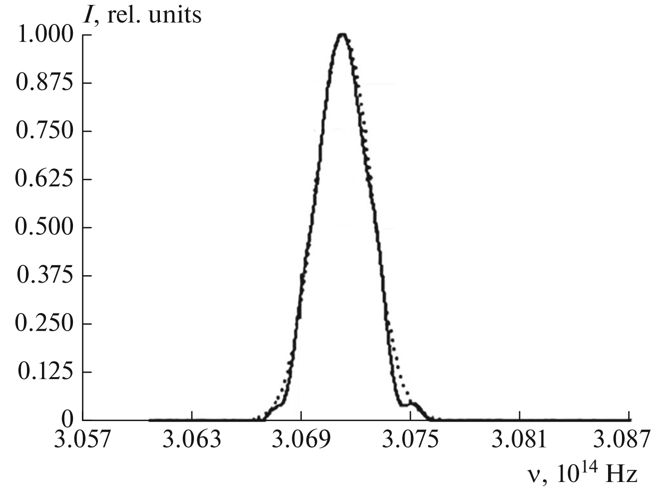

Fig. 1. Contour of line $f_{\text{cal}.1}\left(\frac{\nu-\nu_{01}}{\Delta\nu_1}\right)$ enveloping the radiation spectrum in the first lasing channel of an ATC-C200-100-980 laser diode with an operating time of 350 h at a pumping current of 940 mA.

The form of function $f_{\exp}(\nu)$ (and hence functions $f_{\text{cal}.i}\left(\frac{\nu-\nu_{0i}}{\Delta\nu_i}\right)$) depended on the LD pumping current. Analysis of calculated functions $f_{\text{cal}.i}\left(\frac{\nu-\nu_{0i}}{\Delta\nu_i}\right)$ shows that all three lines were symmetric with respect to frequencies ν_{01}, ν_{02}, and ν_{03} only at a certain value of the pumping current. And only at this value of current can calculated functions $f_{\text{cal}.i}\left(\frac{\nu-\nu_{0i}}{\Delta\nu_i}\right)$ be approximated by a Gaussian function, as is shown in Fig. 1.

A fourth lasing channel appeared in the LD radiation spectrum (Fig. 2a) for pumping current $I = 940$ mA ($I = 1.89I_{\text{th}}$) and when the LD operating time had grown to 350 h. According to (2), this means the length of LD coherence continued to diminish up to $L_{\text{coh}} = 1.4$ cm. Raising the number of nonphased channels led to a corresponding increase in the number of spectral components of LD radiation. This was because the gain band had a fairly wide (5 nm in wavelength and 1.6 THz in frequency) spectral width and had to be filled with new emission bands correspond-

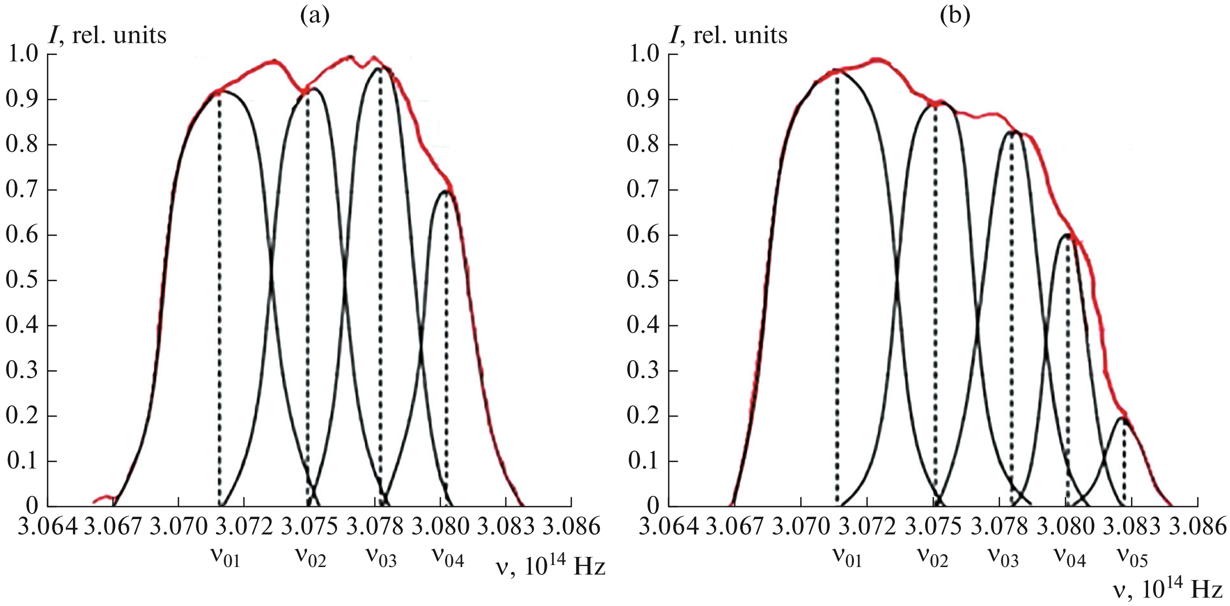

Fig. 2. Emission spectrum $f_{\mathrm{exp}}(\nu)$ of an ATC-C200-100-980 laser diode with an operating time of 350 h for two characteristic values of the pumping current: (a) $I_{\mathrm{p.1}} = 940$ mA; (b) $I_{\mathrm{p.2}} = 980$ mA.

ing to different channels until they overlapped considerably. The spectral bandwidth of an individual channel also grew along with their number, as can be seen by comparing Figs. 2a and 2b.

Presenting the LD emission spectrum as the sum of the emission spectra of all lasing channels allowed us to calculate quality parameters A_i in each channel $f_{\mathrm{cal}.i}\left(\frac{\nu-\nu_{0i}}{\Delta\nu_i}\right)$ in the same way as the one used to calculate parameter A of a single-mode laser in [9, 15]. Functions $f_{\mathrm{cal}.i}\left(\frac{\nu-\nu_{0i}}{\Delta\nu_i}\right)$ were analyzed numerically by comparing them to Gaussian functions $f_{\mathrm{G}}\left(\frac{\nu-\nu_{0i}}{\Delta\nu_i}\right)$ within width $\Delta\nu_i$ of the ith line. To perform this an analysis, parameter A_i was introduced into each lasing channel, and its value was calculated with the formula

$$A_i = 1 - \int\limits_{\nu_{1/2i\,\min}}^{\nu_{1/2i\,\max}} \left(\frac{\left| D\left(\frac{\nu-\nu_{0i}}{\Delta\nu_i}\right) - 1 \right|}{\Delta\nu_i} \right) d\nu, \quad (3)$$

where $\nu_{1/2i\,\max}$ and $\nu_{1/2i\,\min}$ are the frequencies determined from the condition

$$f_{\mathrm{cal}.i}\left(\nu_{1/2i\,\min}\right) = f_{\mathrm{cal}.i}\left(\nu_{1/2i\,\max}\right) = f_{\mathrm{G}}\left(\nu_{1/2i\,\min}\right) = f_{\mathrm{G}}\left(\nu_{1/2i\,\max}\right) = 0.5, \quad (4)$$

and

$$D\left(\frac{\nu-\nu_{0i}}{\Delta\nu_i}\right) = \frac{f_{\mathrm{cal}.i}\left(\frac{\nu-\nu_{0i}}{\Delta\nu_i}\right)}{f_{\mathrm{G}}\left(\frac{\nu-\nu_{0i}}{\Delta\nu_i}\right)}, \quad (5)$$

where ν_{0i} is the central frequency of ith spectral frequency range $\Delta\nu_i$, in which the Gaussian function $f_{\mathrm{G}}\left(\frac{\nu-\nu_{0i}}{\Delta\nu_i}\right)$ and function $f_{\mathrm{cal}.i}\left(\frac{\nu-\nu_{0i}}{\Delta\nu_i}\right)$ are equalized.

Frequency ν_{0i} is defined by the formula

$$\nu_{0i} = \frac{1}{2}\left(\nu_{1/2i\,\max} + \nu_{1/2i\,\min}\right). \quad (6)$$

The normalized Gaussian function is

$$f_{\mathrm{G}}\left(\frac{\nu-\nu_{0i}}{\Delta\nu_i}\right) = \exp\left[-4\cdot\ln 2\left(\frac{\nu-\nu_{0i}}{\Delta\nu_i}\right)^2\right]. \quad (7)$$

It follows from (3) and (5) that the value of parameter A_i tends to unity when function $f_{\mathrm{cal}.i}\left(\frac{\nu-\nu_{0i}}{\Delta\nu_i}\right)$ can be approximated by Gaussian function (7).

When the number of lasing channels is raised, the number of functions $f_{\mathrm{cal}.i}\left(\frac{\nu-\nu_{0i}}{\Delta\nu_i}\right)$ analyzed with (3)–(7) grows as well. However, this does not violate the criterion for determining the LD service life by parameter A_i.

A feature of the studies performed in this work was that the lines with central frequencies ν_{0i} enveloping the LD emission spectrum were analyzed at fixed values of laser operating time in a wide range of values of its pumping current: from 940 to 980 mA. The choice of this range was due considerable transformation of the LD radiation spectrum being observed in these limits.

Four lasing channels were observed at 350 h of operation, and there were already five channels at a pumping current of 980 mA (Fig. 2b). The emergence of the fifth lasing channel led to the part of the radiation energy being redistributed between the four lasing channels entering the fifth channel with central frequency ν_{05}, which explains the transformation of the radiation spectrum. Figure 1 shows the contour of the first lasing line at an LD pumping current of 940 mA with a central frequency of 3.072×10^{14} Hz. We can see that curve $f_{\text{cal.1}}\left(\frac{\nu-\nu_{01}}{\Delta\nu_1}\right)$ coincides almost entirely with function $f_{\text{G}}\left(\frac{\nu-\nu_{01}}{\Delta\nu_1}\right)$. A similar picture is observed for all four lasing contours in Fig. 2a. It follows that an LD pumping current of 940 mA is optimal, and further observations of its slow degradation should be made at this level of current.

Numerical analysis of functions $f_{\text{cal.}i}\left(\frac{\nu-\nu_{0i}}{\Delta\nu_i}\right)$ in all four lasing channels at $i = 1, 2, 3$, and 4 showed that the corresponding values of A_i range from 0.93 to 0.95. It follows that the mode of radiation generation in each channel was close to single, and a multimode radiation beam can be presented formally as the simultaneous generation of unsynchronized single-mode beams. It follows from the theory of diffraction that the dephasing of individual ranges of laser radiation inside the LD cavity should grow along with the number of lasing channels (a reduction in the transverse dimensions of each channel). This is a consequence of the shorter length of radiation coherence in each LD channel. It is thus expedient to use the observed number of lasing channels, which can be judged from the number of lines in the measured LD emission spectrum, as a criterion for the degradation of a particular laser.

The procedure for a quantitative analysis of function $f_{\exp}(\nu)$ was the same for all high-power LDs considered in this work, so it is considered in detail using the example of an ATS-S200-100-980 laser diode with an LDD-10 driver.

Of particular interest are the results from a quantitative analysis of function $f_{\exp}(\nu)$, which describes the shape of the line enveloping the emission spectrum of KLM-H980-200-5 lasers with a radiation power of 200 mW. For this LD modification, it was found that three lasing channels were observed as early as the first hours of their operation.

According to the investigations performed in this work, this indicates low coherence of radiation, and thus an initially low quality of the laser heterostructures of the KLM-H980-200-5 model. A numerical analysis of functions $f_{\text{cal.}i}\left(\frac{\nu-\nu_{0i}}{\Delta\nu_i}\right)$ in all three lasing channels was performed for these devices using the values $i = 1, 2$, and 3. It was done by comparing this function to the Gaussian $f_{\text{G}}\left(\frac{\nu-\nu_{0i}}{\Delta\nu_i}\right)$ in the width of the ith line using formulas (3)–(7). The analysis showed that none of curves $f_{\text{cal.}i}\left(\frac{\nu-\nu_{0i}}{\Delta\nu_i}\right)$ were symmetric with respect to the corresponding central frequencies of the channels, calculated using formula (6). We then decided to use the optimum value of the pumping current at which the asymmetry of curves $f_{\text{cal.}i}\left(\frac{\nu-\nu_{0i}}{\Delta\nu_i}\right)$ is minimal.

It should be noted that decomposing the emission spectrum into its components became much more complicated, due to the asymmetry of curves $f_{\text{cal.}i}\left(\frac{\nu-\nu_{0i}}{\Delta\nu_i}\right)$, and additional iterations were required to satisfy condition (1). The curves had a fairly complex shape, resulting in low values of parameters A_i even at the optimum pumping current. The characteristic values of these parameters varied from 0.82 to 0.86. The service life of the KLM-H980-200-5 LD model was determined as in [10]. Out of four calculated values, the minimum one of parameter A was used in our calculation formula.

CONCLUSIONS

It was established that the number and quality of the spectra of radiation lasing channels can be used as a parameter by which we can determine the state and rate of LD degradation with a certain operating time. It is shown that the increase in the number of lasing channels was due to a reduction in the length of LD radiation coherence, which is a clear sign of laser degradation.

The rate of degradation grew along with the pumping current. This was confirmed by the ignition of an additional channel of LD generation at a fixed time of its operation. An algorithm for determining the optimum pumping current was developed. In developing this algorithm, it was considered that the LD emission spectrum was a superpositioning of the emission spectra of individual lasing channels. Analysis of the emission spectrum in each lasing channel allowed us to determine the value of parameter A_i, which characterizes the difference between the line contour enveloping the emission spectrum in the channel and a Gaussian function. If all values of parameter A_i are close to unity, this testifies to the high quality of the LD heterostructure.

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Translated by G. Dedkov