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# Fine and Rough Structures of the Frequency Spectrum of a High-Power Laser Diodes during Slow Degradation

**V. V. Bliznyuk[a, *], V. A. Parshin[a], A. G. Rzhanov[b], O. I. Semenova[a], and A. E. Tarasov[a]**

[a] *Moscow Power Engineering Institute, Moscow, 111250 Russia*

[b] *Faculty of Physics, Moscow State University, Moscow, 119991 Russia*

**e-mail: 40595141@mail.ru*

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**Abstract**—It is shown that fine and rough structures can be differentiated in the radiation spectrum of a powerful laser diode. The relationship between the spectrum's characteristics and the internal parameters of the laser's structure is established and verified experimentally during degradation of the device. The effect of losses in the resonator and the coherence of laser radiation on both fine and rough structures of the radiation spectrum is shown.

**Keywords:** semiconductor laser, high-power laser diode, frequency spectrum, degradation, coherence

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## INTRODUCTION

Due to the rapid development of technology for manufacturing high-power semiconductor laser diodes (PLDs), we can now improve their technical parameters considerably and thus expand the scope of PLD applications [1]. The effectiveness of using PLDs depends largely on its most important technical and economic parameter: the service life. Great attention is therefore given to developing new ways of predicting the service lives of PLDs.

A number of ways have already been developed for monitoring the condition of PLDs and predicting their service life time [2–11]. The classical technique based on measuring the emission power of an PLD at a constant pump current is used most often. The service life time is in this case defined as the time after which the power drops to a certain predetermined level [9].

Another technique is associated with measuring the radiation power of PLDs, where the operating time is defined as the period after which it is impossible to maintain the power at a constant level by increasing the pump current [9]. Procedures based on the temporal dependence of the radiation pattern [10] and analyzing those of the linear polarization of radiation (contrast) [11] are used much less often to predict the service life time of PLDs.

The techniques discussed above allow us to determine the service life time of a certain number of copies from a batch of PLDs, and then extrapolate the results to the entire batch [6]. However, their implementation requires the consumption of a great many laser resources and the use of statistical means of processing large amounts of data.

The first signs of PLD degradation appear after 2000 to 3000 h of operation. The accelerated aging of devices at elevated ambient temperatures is therefore used for diagnostics. The resource of PLD is rapidly consumed during accelerated aging tests, preventing us from solving the problem of determining the quality of a particular PLD without using a large part of the laser resource [12].

## DETERMINING THE STATE OF THE HETEROSTRUCTURE OF A POWERFUL PLD FROM THE NUMBER OF CHANNELS OF GENERATION

Steps to solve this problem were taken in [3] when testing a batch of PLD manufactured in a single technological cycle. The state of the PLD heterostructure was determined from the number of channels of generation. At the same time, earlier ways of determining the state of an PLD heterostructure from its spectrum can be used only if lasing occurs on the fundamental mode [3]. However, an PLD is characterized by a complex emission spectrum. This spectrum was therefore analyzed by decomposing it into quasi–single-mode components and subsequently studying their temporal transformation. It was shown that the number of lasing channels grows because the length of the coherence of PLD radiation is reduced—a clear sign of laser degradation [3].

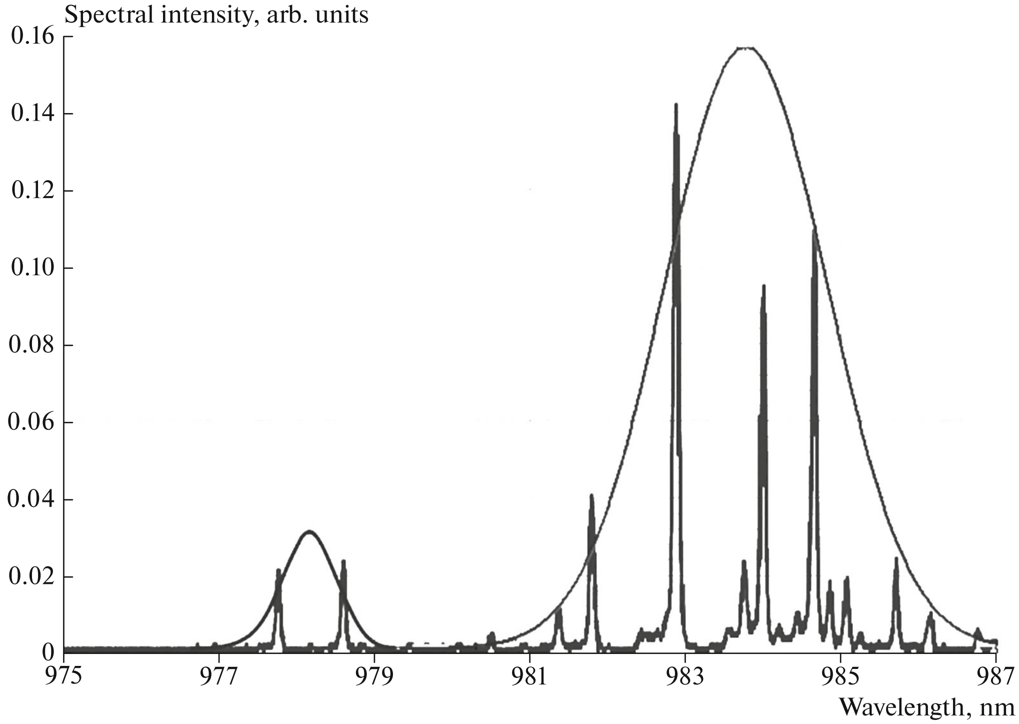


**Fig. 1.** Spectral characteristics of KLM-H980-120-5 PLD 129 at the initial stage of operation.

## RESULTS FROM STUDYING THE CONDITION OF A BATCH OF POWERFUL KLM-H980-120-5 PLDs

In experiments conducted over the past year, we analyzed laser degradation based on both the rough and fine structures of the spectrum for the first time. We studied the emission spectrum of five KLM-H980-120-5 PLDs manufactured in a single technological cycle. According to their technical data sheets, the lasers had serial numbers 126, 127, 128, 129 and 130. Each spectrum was measured after 10 h of operation and 90 h of accelerated aging tests at a temperature of 45°C (equivalent to 250 h of normal operation). An MDR-23 spectrometer with a wavelength resolution of 0.05 nm was used to measure the spectra.

All five PLDs had standard radiation power $P =$ 120 mW at a standard pump current of 300 mA. Threshold currents varied from 74.6 to 75.3 mA.

Let us consider the degradation of PLD 129 as an example. Figures 1 and 2 show the spectra of this device before and after 250 h of normal operation. We can see that the emission spectrum of PLD 129 lies in the range specified in its passport: 980 ± 5 nm. The emission spectra of the remaining PLDs are in the same range of wavelengths. The spectra mainly consist of equidistant lines, which is typical of Fabry–Perot resonators. This allows us to define the fine structure of the spectrum as one consisting of groups of high-intensity peaks of the PLD's longitudinal modes. The envelopes of such groups of peaks represent elements of the rough structure of the PLD spectrum that correspond to different spatial channels of generation that we considered in [5, 6]. Two processes were observed during the degradation of PLD 129: the emergence in the rough spectrum of two new envelopes of a group of high-intensity peaks, and an increase in the spectral width of the lines of longitudinal modes. Figure 2 also shows that the lines of the fine structure of the spectrum—the resonances of longitudinal modes—grew simultaneously inside the envelopes. Note that the total number of the considered PLD's generated longitudinal modes grew to several tens as it degraded.

At the start of testing the batch of lasers, the operating time of the devices was no more than 10 h. An analysis of the emission spectra of five PLDs showed that one and two lasing channels could be distinguished in the emission spectra of lasers with serial numbers 126 and 129, respectively, while three lasing channels could be distinguished in the emission spectra of lasers with serial numbers 127, 128, and 130.

After 90 h of accelerated testing of the batch of lasers, one lasing channel remained in the spectrum of PLD 126; as noted above, two more lasing channels appeared in the spectrum of PLD 129 (Fig. 2). The number of channels of generation in PLDs with serial numbers 127, 128, and 130 also rose to four. An increase in the number of lasing channels was thus observed for all PLDs except 126.

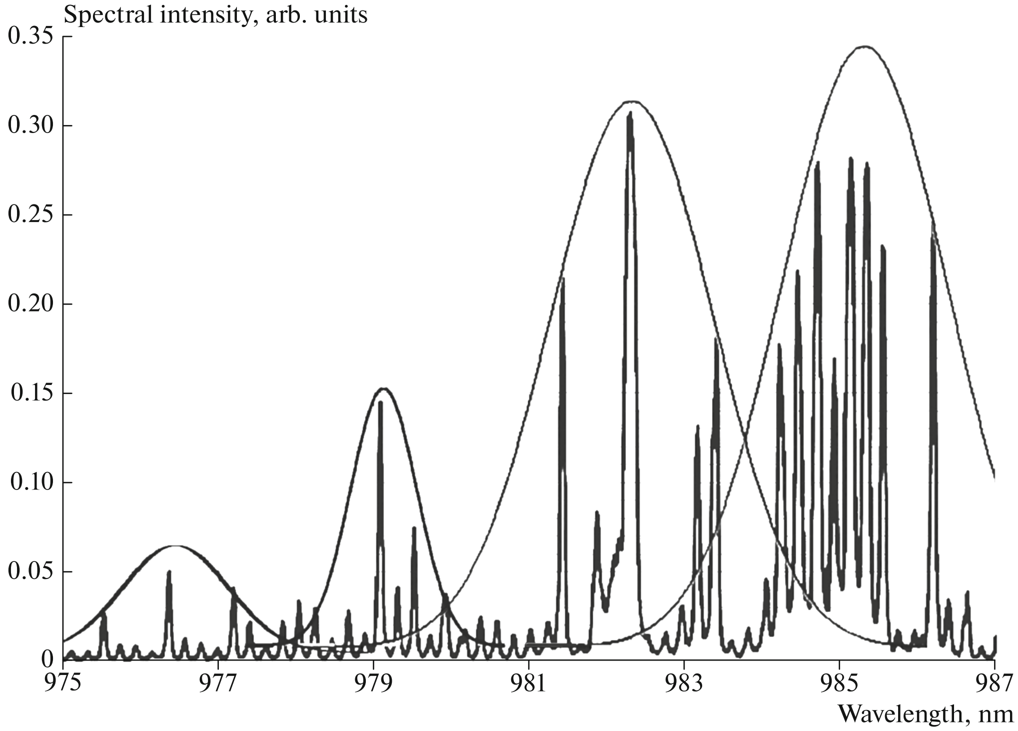


**Fig. 2.** Spectral characteristics of KLM-H980-120-5 PLD 129 after 90 s of accelerated aging tests.

In our opinion, the decay of radiation into individual channels of generation as theit number grew indicates deterioration in the state of the heterostructure. It is characteristic that this decay occurs at the initial stage of laser operation. This shows the way of determining the state of the heterostructure of a specific serial high-power diode laser through the number of radiation channels of generation can be used for fast, resource-saving diagnostics of diode laser radiation.

As will be shown below, this is explained by losses $\alpha_{internal}$ in the resonator growing along with degradation, so average length of coherence $L_{coh}$ of the radiation of longitudinal modes is reduced [5].

A detailed study of PLD spectra allows us to determine changes in the coefficient of internal losses and the average length of coherence of PLD radiation during degradation, and to draw conclusions about such laser parameters as length $L$ of the cavity, width $W$ of the active region, thickness $d$ of quantum wells, average effective refractive index $n_{eff}$ of the laser waveguide, and coefficients $R_1$ and $R_2$ of mirror reflection. The accuracy will in this case be 10–20%, which is nevertheless quite suitable for estimates. Due to the fairly wide technological scatter in the material and geometric parameters of a multilayer PLD structure, such accuracy of estimates can be considered satisfactory. To be definite in our estimates, we will take values $R_1$ = 0.3, $R_2$ = 0.98, and $n_{eff}$ = 3.6 characteristic of PLDs based on InGaAs compounds and designed for radiation wavelengths in the range of 950–1000 nm, depending on the proportions of the atoms composing the layers [8]. The choice of coefficients of reflection is discussed below. To be definite, we shall focus on the spectra of PLD 129.

## SPECTRA AND DIMENSIONS OF THE ACTIVE REGION OF A LASER CAVITY

### *Longitudinal Modes (Fine Spectrum)*

Measurements showed that the distance between longitudinal Fabry–Perot modes was on average $\Delta\lambda_{FP} \approx 0.4$ nm. This corresponded to resonator length $L = 330$ μm and $\lambda_0 = 980$ nm, according to the familiar relation

$$L \approx \frac{\lambda_0^2}{2n_{eff}\Delta\lambda_{FP}}, \tag{1}$$

which corresponds to the longitudinal mode with number $M = 2445$:

$$M \approx \frac{2n_{eff}L}{\lambda_0}, \tag{2}$$

or

$$M \approx \frac{\lambda_0}{\Delta\lambda_{FP}}. \tag{3}$$

The widths of spectral peaks of longitudinal modes $\Delta\lambda_{res}$ at half intensity can be determined only approximately from the data we have: $\Delta\lambda_{res} \approx 0.08–0.11$ nm. This value is related to quality factor $Q_x$ and internal losses $\alpha_{internal}$ of a cold PLD resonator [13]:

$$Q_x = \frac{\lambda_0}{\Delta\lambda_{res}}, \quad (4)$$

$$Q_x = M\pi\left(L\alpha_{internal} + \frac{1}{2}\ln\frac{1}{R_1R_2}\right)^{-1}, \quad (5)$$

where from (4) we obtain $Q_x = 8900–12250$. Let us determine the values of $\Delta\lambda_{res}$ and $Q_x$ more accurately. Provided there are no internal losses ($\alpha_{internal} = 0$ cm$^{-1}$), from (5) we obtain possible coefficients of mirror reflection within limits $R_1 \times R_2 = 0.2–0.5$. We now write $R_1 = 0.3$ and $R_2 = 0.98$, which corresponds to when the first mirror has no reflective coating, while the second has almost complete reflection. This option seems quite realistic from the viewpoint of PLD manufacturability, so we will consider it to be the limit point in terms of losses. According to (5), this set of parameters corresponds to maximum quality factor $Q_x \approx 12\,545$ at $\alpha_{internal} = 0$ cm$^{-1}$ and $\Delta\lambda_{res} \approx 0.078$ nm. The true picture of PLD operation corresponds to $\alpha_{internal} > 0$ cm$^{-1}$, so $Q_x \approx 9860$ if the initial values of internal losses are, e.g., $\alpha_{internal} = 5$ cm$^{-1}$. This corresponds to $\Delta\lambda_{res} \approx 0.099$ nm, which is quite consistent with the measured values. We have thus determined possible values of the parameters: $R_1 = 0.3$, $R_2 = 0.98$, and $\alpha_{internal} = 5$ cm$^{-1}$. We will use these values in further estimates.

### *Channels of Generation (Rough Spectrum)*

We found that the frequency spectrum of an PLD consists of several groups of lines whose widths and quality factors are determined by losses $\alpha_{internal}$ in the resonator and coefficients of mirror reflection $R_1$ and $R_2$ (5). Each spectral group corresponds to one of the spatial channels of generation, number $N_{chan}$ of which depends on average length of coherence $L_{coh}$ of radiation in the channel and width $W$ of the active region [14]:

$$N_{chan} \approx W\sqrt{\frac{2\pi n_{eff}}{\lambda_0 L_{coh}}}. \quad (6)$$

From these we obtain the length of coherence:

$$L_{coh} \approx \frac{2\pi n_{eff}}{\lambda_0}\left(\frac{W}{N_{chan}}\right)^2, \quad (7)$$

where $\lambda_0 = 980$ nm is the average wavelength of PLD radiation in a vacuum.

We can see two groups of radiation modes in Fig. 1, so we will assume there are two channels of generation. We do not know exactly the width of the region of generation, but we will try to estimate it on the basis of certain considerations. Let us first estimate the average length of coherence of PLD radiation, based on values $Q_x = 9860$ and $\Delta\lambda_{res} \approx 0.099$ nm:

$$L_{coh} \approx Q_x\lambda_0, \quad (8)$$

from which we obtain $L_{coh} = 0.97$ cm.

We can now use relations (5), (6) to determine the widths of the lasing channels and thereby estimate the entire width of the PLD's active region [14, 15]:

$$w_0 = \sqrt{\frac{\lambda_0 L_{coh}}{2\pi n_{eff}}}, \quad (9)$$

$$W = N_{chan}\sqrt{\frac{\lambda_0 L_{coh}}{2\pi n_{eff}}}. \quad (10)$$

We earlier found there were two channels of generation ($N_{chan} = 2$) at the beginning of our study. Based on relations (5), (8), (9), we therefore obtained the width $W \approx 40$ μm of the PLD's area of generation and width $w_0 \approx 20$ μm of one lasing channel.

### *Quantum Well Layer Thickness*

The use of quantum wells as an active layer was due to the energy band in which nonequilibrium carriers are concentrated being $10^2–10^3$ times thinner than that of the bulk active layer. The thickness of the quantum well uniquely determines the maximum width of the PLD spectrum. In the spectra shown in Figs. 1 and 2, widths $\Delta\lambda_{gen} \approx 8–10$ nm, which for the considered PLD parameters corresponds to the spatial thickness of the quantum well $d_{QW} \approx 18–20$ nm.

We have thus approximately determined the type of an PLD and the basic characteristics of its structure, based on experimental data on its laser spectrum (Fig. 1).

## SPECTRUM AND PARAMETERS OF AN PLD AFTER OPERATION

Let us turn to Fig. 2. As noted above, we observe several key features associated with PLD degradation. The first of these is the emergence in the spectrum of a large number of new peaks that no longer form two but four groups of lines of radiation responsible for channels of generation ($N_{chan} = 4$). The second is the spectral lines of longitudinal modes broadening along with enrichment of the spectrum. The third is the emergence of non-equidistant components of the spectrum that are responsible for either lateral modes or interaction between channels. We shall focus on the first two features.

The simplest explanation for the transformation of the spectrum during PLD degradation is that constant heating of the region of the quantum wells where radiation is generated causes dislocations in its crystal structure and the adjacent layers, the number of which grows over time. This first increases internal losses $\alpha_{\text{internal}}$ and then alters the parameters calculated in the previous section.

Quantities $W = 40$ μm, $L = 330$ μm, $R_1 = 0.3$, and $R_2 = 0.98$ cannot change. Quantities $M = 4995$, $d_{QW} = 18$ nm, and $n_{\text{eff}} = 3.6$ are average values, so they change negligibly. Only the values of $\Delta\lambda_{\text{res}}$ and $N_{\text{chan}}$ change appreciably, along with associated $L_{\text{coh}}$, $Q_x$, and $w_0$.

Let us start with $N_{\text{chan}} = 4$. Using formulas (3)–(9) gives us new values of the radiation parameters: $L_{\text{coh}} = 0.68$ cm (6), $Q_x = 6900$ (7), $w_0 \approx 10$ μm (8), and $\Delta\lambda_{\text{res}} \approx 0.142$ nm (4).

To calculate internal losses, we use a formula obtained from relations (1)–(8):

$$\alpha_{\text{internal}} = \frac{\lambda_0}{w_0^2} - \frac{1}{2L}\ln\frac{1}{R_1R_2}. \quad (11)$$

When deriving relation (10), we also used the expression for constant of propagation $\beta_M$ of the fundamental longitudinal mode of order $M$ [14],

$$\beta_M = \frac{M\pi}{L} + \frac{i}{2}\left[\alpha_{\text{internal}} + \frac{1}{2L}\ln\left(\frac{1}{R_1R_2}\right)\right], \quad (12)$$

and another expression for quality factor $Q_x$:

$$Q_x = \frac{\text{Re}(\beta_M)}{2\,\text{Im}(\beta_M)}. \quad (13)$$

After operating the PLD, we obtained $\alpha_{\text{internal}} = 79$ cm$^{-1}$, $Q_x = 6900$, and $\Delta\lambda_{\text{res}} \approx 0.142$ nm instead of $\alpha_{\text{internal}} = 5$ cm$^{-1}$, $Q_x = 9860$, and $\Delta\lambda_{\text{res}} \approx 0.099$ nm. All of the indicated values correspond to experimental data.

However, the above values are of an approximate nature. If more detailed information becomes available on the composition of the semiconductor layers and the geometry of the PLD, our set of theoretical calculations will give a more accurate picture of the physical processes and patterns that emerge during the long-term operation of high-power lasers.

## CONCLUSIONS

There is a considerable increase in internal losses during the degradation of an PLD, which is expressed in deterioration of the coherence of the radiation, the enrichment of the radiation spectrum, the emergence of new spatial structures in the form of new channels of generation unrelated in phase, and the broadening of the spectral lines of longitudinal modes. We demonstrated these phenomena experimentally.

We established two new factors that can be used to quickly diagnose the life of a laser diode, based on its emission spectrum: the spectral width of an individual longitudinal mode and the number of peaks in the rough structure of the spectrum. The simultaneous use of two (with a power of three) aging criteria would greatly improve the reliability and accuracy of determining the start of degradation that is unacceptable for a given device, and the associated need to replace the PLD.

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## CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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