ISSN 1062-8738, Bulletin of the Russian Academy of Sciences: Physics, 2018, Vol. 82, No. 11, pp. 1367–1370. © Allerton Press, Inc., 2018.
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Estimating the Operational Lifespan of Transverse Single-Mode Laser Diodes from Their Spectral Characteristics

V. V. Bliznyuk[a, *], **O. I. Koval**[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*
***e-mail: rjanov@mail.ru*

Abstract—A way of predicting the operational lifespan of transverse single-mode laser diodes, based on analyzing the form factor of the envelope of its emission spectrum at the initial stage of operation, is proposed.

DOI: 10.3103/S1062873818110084

INTRODUCTION

The extensive use of transverse single-mode laser diodes (LDs) makes the problem of predicting their operational lifespan relevant. The most common way of solving this problem is based on measuring the time dependences of the LD pumping current needed to maintain the radiation power at a required level [1]. Complex measurements of the time dependences of the beam and LD emission spectrum profiles are also used [2–5]. Special attention is given to the problem of coordinating the distribution of emission intensity in the far-field region and the Gaussian function, and to the shape of the peaks corresponding to higher-order modes in the emission spectrum.

A relatively recent approach based on measuring the LD emission contrast at the initial stage of operation (during the first 50–100 hours of operating time) [6] appears promising. Analysis of the LD emission parameters at the initial stage of operation allows us to obtain information concerning LD heteroctructure, even though premature death is the dominant mechanism of its degradation at that stage [1]. An undeniable advantage of this approach is the possibility of predicting an LD's operational lifespan quite quickly, without unproductive use of its resource.

In light of the advantages of rapid diagnostics of a LD's heterostructure, we propose a way of predicting LD lifespan based on analyzing the form factor of the envelope of the LD emission spectrum at the initial stage of operation.

INSTRUMENTATION FOR MEASURING LD SPECTRAL CHARACTERISTICS

Our approach is based on using an MDR-23 monochromator, a spectral instrument with low resolution. The use of such an instrument does not allow us to measure the fine structure of emission spectrum, i.e., the emission lines corresponding to the longitudinal mode of a Fabry–Perot resonator. However, the MDR-23's resolution is sufficient for determining with high accuracy the form factor of the emission spectrum envelope.

The spectral characteristics were determined experimentally using an emission wavelength scale and then a frequency scale, considering the well-known relation between the emission wavelength and frequency.

An analog signal from a photodiode positioned behind the monochromator's output slit was applied to the plate of the NI-USB 6008 32-bit analog-to-digital converter connected to it. The use of this plate allowed us to construct a measuring complex based on the spectral instrument, i.e., to scan in a required spectral range with a given scanning pitch and detect a signal from the photodetector simultaneously. The output signal from the plate is fed directly to a computer with NI SignalExpress software installed. As a result, we can obtain a set of numbers displayed visually on the monitor screen in the form of LD spectral characteristics.

RESULTS FROM MEASURING THE SPECTRAL CHARACTERISTICS OF LDs GENERATING IN THE RED SPECTRAL RANGE

Investigating the form factors of emission spectrum envelopes of more than 100 LD samples generating radiation at wavelengths of 0.635 and 0.65 μm, we established that functions $f_{\text{exp}}(\nu)$ describing them vary within wide limits.

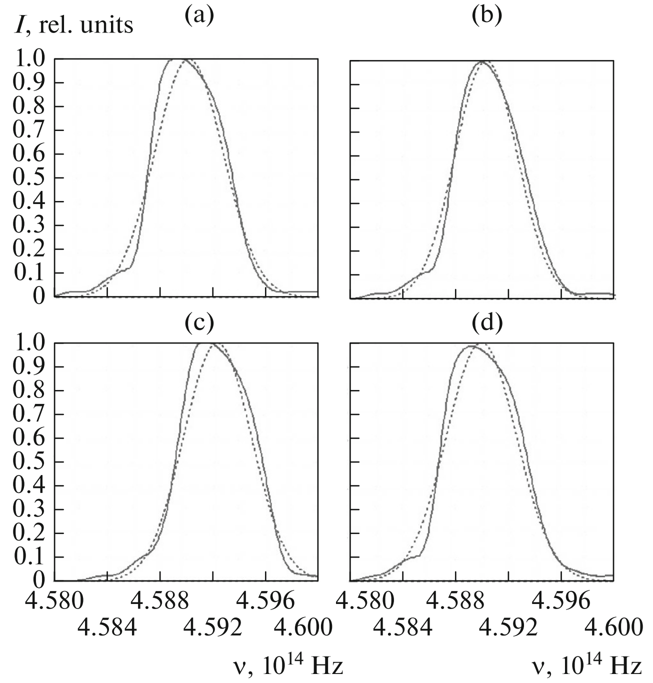

Fig. 1. Spectral characteristics of LD 1, shown by the solid line at pumping current values of (a) $1.05I_{\text{th}}$; (b) $1.07I_{\text{th}}$; (c) $1.1I_{\text{th}}$; (d) $1.15I_{\text{th}}$. The dotted line is a Gaussian function.

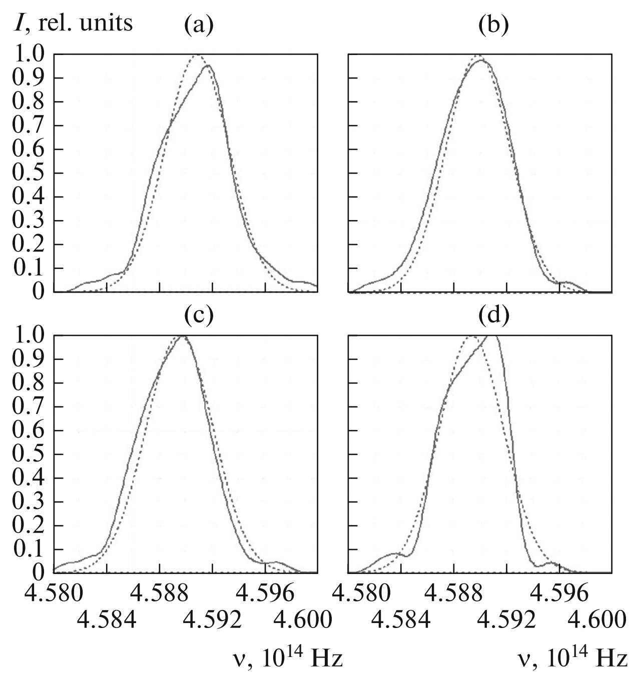

Fig. 2. Spectral characteristics of LD 3, shown by the solid line at pumping current values of (a) $1.05I_{\text{th}}$; (b) $1.075I_{\text{th}}$; (c) $1.15I_{\text{th}}$; (d) $1.19I_{\text{th}}$. The dotted line is a Gaussian function.

In light of the variation in function $f_{\text{exp}}(\nu)$, three parameters were used in this work to analyze each sample:

(1) The width of the emission spectrum envelope $\Delta\nu$, calculated according to the formula

$$\Delta\nu = \nu_{1/2\max} - \nu_{1/2\min}, \tag{1}$$

where $\nu_{1/2\min}$ and $\nu_{1/2\max}$ are the minimum and maximum emission frequencies at which the value of function $f_{\text{exp}}(\nu)$ is 0.5.

(2) Central frequency ν_0 of this spectral range:

$$\nu_0 = 0.5(\nu_{1/2\max} + \nu_{1/2\min}). \tag{2}$$

(3) Frequency $\nu_{\text{exp max}}$, at which the value of the function $f_{\text{exp}}(\nu)$ is maximum.

A considerable dependence of the form of function $f_{\text{exp}}(\nu)$ on the pumping current was observed for LDs generating in the red spectral range (Figs. 1 and 2).

It was thus established for a set of 20 LDs generating at a wavelength of 0.65 μm that at a pumping current of $1.05I_{\text{th}}$, where I_{th} is the value of the threshold current, frequency $\nu_{\text{exp max}}$ was lower than ν_0 (Fig. 1a). At a pumping current of $1.07I_{\text{th}}$, frequency $\nu_{\text{exp max}}$ was virtually equal to ν_0 (they differed by no more than 0.08%) (Fig. 1b). At higher pumping currents, frequency $\nu_{\text{exp max}}$ was once again lower than frequency ν_0 (Figs. 1c, 1d).

For the second set of 35 LDs generating at a wavelength of 0.65 μm, frequency $\nu_{\text{exp max}}$ was higher than ν_0 at a pumping current of $1.05I_{\text{th}}$, (Fig. 2a). At a pumping current equal to $1.075I_{\text{th}}$, frequency $\nu_{\text{exp max}}$ was virtually equal to ν_0 (they differed by no more than 0.09%) (Fig. 2b). At higher pumping currents, frequency $\nu_{\text{exp max}}$ was once again higher than ν_0 (Figs. 1c, 1d).

In the regime of LD generation where condition $\nu_{\text{exp max}} = \nu_0$ was satisfied, function $f_{\text{exp}}(\nu)$ became symmetrical with respect to the frequency $\nu_{\text{exp max}}$, and we could approximate function $f_{\text{exp}}(\nu)$ with an even function or a sum of even functions with central frequency ν_0 coinciding with frequency $\nu_{\text{exp max}}$. The heterostructure of LDs and their emission spectra were in this case analyzed using Lorentz and Gaussian functions [7]. However, using the symmetrical contours of the Epstein profile [7]

$$Ep(x, n) = \left[\operatorname{sech}(x/n)\right]^n, \tag{3}$$

the Fourier transform of which allows a smooth transition from Lorentz contour $f_{\text{L}}(\nu)$ to Gaussian $f_{\text{G}}(\nu) = \exp\left[\pi\left(\dfrac{\nu - \nu_0}{\Delta\nu}\right)^2\right]$, often produces a satisfactory result.

Table 1. Dependence of ratio $\tau/\tau_{\max}$ on $A(\tau,\nu)$, where $\tau_{\max}$ is the maximum operational lifespan of LDs whose $f_{\exp}(\nu)$ is approximated by a Gaussian curve

$A(\tau,\nu)$	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
$\tau/\tau_{\max}$	0.20	0.35	0.48	0.60	0.70	0.80	0.86	0.91	0.95	0.98	1.00

If condition $\nu_{\exp\max} = \nu_0$ is not satisfied, the form factors of the emission spectrum envelope are not symmetrical with respect to emission frequency $\nu_{\exp\max}$, and function $f_{\exp}(\nu)$ cannot be approximated by an even function with central frequency ν_0 coinciding with frequency $\nu_{\exp\max}$. This greatly complicates predicting an LD's operational lifespan on the basis of this function.

It was established that provided condition $\nu_{\exp\max} = \nu_0$ is satisfied, the contour of the LD spectrum envelope at an emission wavelength of 0.65 μm is described by the function

$$F_S(\nu) = 0.5\left[F_G + \operatorname{sech}^8\left(\frac{\nu-\nu_0}{\Delta\nu}\right)\right] \qquad (4)$$

at ν lower than ν_0, and by

$$F_S(\nu) = 0.5\left[F_G + \operatorname{sech}^4\left(\frac{\nu-\nu_0}{\Delta\nu}\right)\right] \qquad (5)$$

at ν higher than ν_0.

Generalizing (4) and (5), we can write F_S in the form

$$F_S(\nu) = 0.5\left[F_G + \operatorname{sech}^n\left(\frac{\nu-\nu_0}{\Delta\nu}\right)\right], \qquad (6)$$

where $n = 8$ or 4.

On the other hand, $f_{\exp}(\nu)$ can be written in the form

$$f_{\exp}(\nu) = A(\tau,\nu)f_G(\nu) + (1 - A(\tau,\nu))f_{\operatorname{sech}}(\nu), \qquad (7)$$

where $f_{\operatorname{sech}}(\nu) = \operatorname{sech}\left(\frac{\nu-\nu_0}{\Delta\nu}\right)$. The value of the coefficient $A(\tau,\nu)$, determined empirically from the form of the emission line envelope, varies from 0 to1; and τ is the predicted LD operational lifespan.

Within limits of ratio $(\nu-\nu_0)/\Delta\nu$ from –4 to +4, coefficient $A(\tau,\nu)$ virtually does not depend on frequency ν, and its value characterizes parameter τ.

It was established that τ has a minimum value at $A(\tau,\nu)$ equal to zero. A monotonous increase in τ is observed as $A(\tau,\nu)$ grows. The dependence of ratio $\tau/\tau_{\max}$ on $A(\tau,\nu)$, where $\tau_{\max}$ is the maximum operational lifespan of the LDs whose $f_{\exp}(\nu)$ is approximated by a Gaussian curve, is presented in Table 1.

Maximum operational lifespan $\tau_{\max}$ is thus observed for the LDs whose measured function $f_{\exp}(\nu)$ after times of operation not exceeding 50 h has a Gaussian form.

It should be noted that the directional patterns of such LDs at the initial stage of operation also have the Gaussian profile [5] characteristic of single-mode lasers. In addition, they have high degrees of linear polarization (above 0.9) [4].

It is known that upon violation of the single-mode generation regime, the profile of an LD radiation beam starts to deviate from the Gaussian distribution [1–3] and its degree of linear polarization at the initial stage of operation does not exceed 0.6–0.7 [6].

The measurements of $f_{\exp}(\nu)$ made in this work showed that the values of coefficient $A(\tau,\nu)$ in this case fall, so predicted LD operatin lifespan τ is reduced as well.

RESULTS FROM MEASURING THE SPECTRAL CHARACTERISTICS OF LDs GENERATING IN THE IR SPECTRAL RANGE

At the initial stage of operation, one contour of the emission spectrum envelope is observed for an IR LD. As the time of operation grows, this contour is transformed to a spectral characteristic with two contours of the envelope (Fig. 3). The second contour is shifted to the longwave region, relative to the one initially registered.

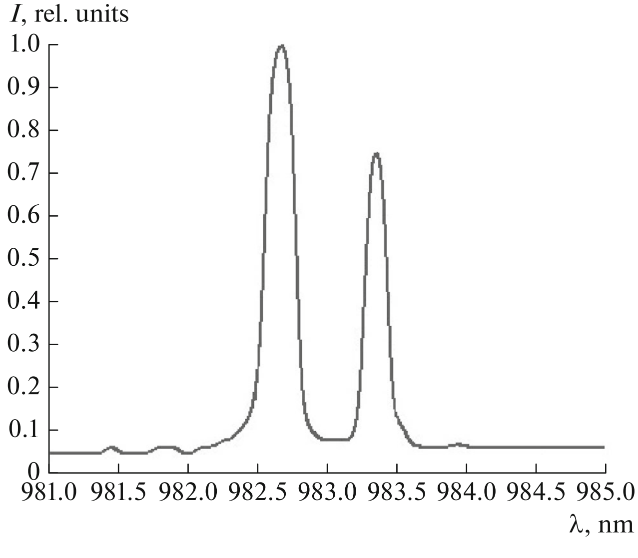

Fig. 3. Emission spectrum of an IR LD at the initial stage of operation (evidence of the short lifespan of such a laser).

Almost all LDs with a generating wavelength of 0.98 μm and one contour of the emission line had an envelope of this contour that was approximated by a Gaussian function. The operational lifespan of such lasers was comparable to those of lasers generating in the red spectral range. At the same time, it was established that the emergence of a second contour of the LD emission spectrum envelope at the initial stage of operation is a clear sign that its structure is imperfect. We may therefore assume that such LDs have extremely short operational lifespans, which is supported by experiments: the operational lifespan of such lasers does not exceed 400 h.

Analysis of the LD emission spectrum during the initial hours of operation thus allows us to distinguish heterostructures of low quality by rejecting those with more than one group of emission lines in the LD spectrum.

RESULTS AND DISCUSSION

LDs with heterostructures of high quality have one envelope of the emission spectrum of longitudinal modes. Both long and short operational lifespans are possible when there is one extremum of the spectral characteristic. The determining factor that can be used to predict an LD's operational lifespan is the form of the line corresponding to function $f_{\exp}(\nu)$. To predict an LD's operational lifespan, we must thoroughly analyze this function using formula (7).

We chose LD groups whose coefficients $A(\tau,\nu)$, determined by means of such analyses, have values within the required ranges. If the spread of values of coefficient $A(\tau,\nu)$ does not exceed 0.02, we can speak about a general value of the predicted life span of LDs belonging to each of these groups.

It is extremely important to note that as function $f_{\exp}(\nu)$ approaches a Gaussian function, the predicted life spans seem to be the limit for the LDs fabricated using the same technology. At the same time, the beam's profile is also determined by a Gaussian function. It means that from the viewpoint of optimizing predicted parameter τ, the preliminary sorting of LDs can start by measuring their radiation pattern. An additional factor is the degree of emission polarization. All LDs with degrees of polarization below 0.9 should be rejected, since their operational lifespans would be very short.

CONCLUSIONS

By determining a concrete value of coefficient $A(\tau,\nu)$ at the initial stage of LD operation, we can estimate operational lifetime τ. By thoroughly analyzing the function describing the form factor, we can perform rapid LD diagnostics.

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Translated by E. Smirnova