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Variations in the output characteristics of broadband superluminescent diodes during long-term operation

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Abstract. **A method of service life tests of SLD-37 quantum-well superluminescent diodes (SLDs), which are widely used in optical coherence tomography, is described and the results of tests are presented. Special attention is given to variations in the emission spectra of SLDs during their aging. It is shown that this method can be used as an incoming test to select processed semiconductor heterostructures with the longest expected lifetime for fabrication of active elements of SLD modules.**

Keywords: *quantum-well heterostructure (nanostructure), superluminescent diode, lifetime, reliability.*

1. Introduction

The leading position among light sources for optical coherence tomography (OCT) systems [1] is occupied by superluminescent diodes (SLDs), which, in addition to the well-known advantages of semiconductor light-emitting devices, have a high brightness and a low degree of coherence, which is very important for OCT. The most widespread Russian devices of this class are light-emitting modules of SLD-37 series based on quantum-well (nanostructured) SLDs of the near-IR spectral region (800–900 nm). These modules, as well as the modules of the advanced SLD-35 series, are used in tens of laboratories and companies involved in research and development of new OCT systems. In addition, SLD-37 modules are used by some companies that produce commercial OCT systems mainly for ophthalmology diagnostics. The total amount of the delivered modules of these series exceeds 10 000 units.

The considered SLDs are made of a separate confinement single quantum well (GaAl)As/GaAs heterostructure [2, 3]. Their active channel is a single-transverse-mode ridge waveguide with a width of 4 μm. The free-space output optical power in the cw regime is 5–35 mW depending on the technical specification. The radiation flux density at the output faces of the crystal is, correspondingly, 1.2–8.5 mW μm^{-1} or 0.12–0.85 MW cm^{-2}. These values are much smaller than the catastrophic optical damage (COD) threshold, which, for these diodes, lies within the range of 3–6 MW cm^{-2}. Extensive statistics shows that, excluding the cases of 'infant mortality' occurring at the initial stage of life tests, instantaneous (catastrophic) failures of these SLDs are observed very seldom.

As to slow degradation (aging), periodic selective life tests showed that the average lifetime for different batches of devices varies from several thousands to several tens of thousands of hours. These values were determined by analysing the time dependences of the output optical power [in the regime of automatic injection current control (ACC)] or of the current [in the regime of automatic output power control (APC)] based on the criteria used for testing laser diodes (LDs). Until recently, this situation was convenient for both customers and manufacturers. However, for some time now, extensive use of OCT systems with these light sources in medicine and other areas accentuated the question. Prediction of the service life (lifetime) of each batch of diodes becomes essential.

It is very important to mention the spectral features of considered SLDs. In contrast to conventional edge-emitting LDs and SLDs based on bulk semiconductor heterostructures, whose spectral profile almost does not change with small variations in the injection current or with aging, these spectral dependences in quantum-well SLDs manifest themselves much stronger. As far as we know, this problem has not been systematically studied. In OCT devices, the spectral width of light sources $\Delta\lambda$ (coherence length $L_{coh} \simeq \lambda^2/\Delta\lambda$), which determines the spatial resolution of tomograms, is the key parameter. The value of $\Delta\lambda$ becomes maximal at a particular working current, when the superluminescence maxima corresponding to the quantum transitions from the ground and excited subbands become equal [4]. It is this current at which SLD modules in OCT systems are usually used. In this case, a strong spectral deformation leading to a decrease in $\Delta\lambda$, which can appear during SLD aging, is inadmissible.

Below, we will consider both power and spectral aging. We will show that spectral aging often occurs faster than power aging. One can expect that the spectrum will be deformed slower in the APC regime rather than in the ACC regime. To confirm this, it is necessary to obtain quantitative results based on adequate statistics.

Studies of the degradation of semiconductor lasers began soon after their creation. Since then, hundreds of original papers and more than ten reviews and monographs on this problem were published (see, for example, [5–10]). Owing to technological progress, the COD threshold and the service life of LDs of different types continue to increase. Nevertheless, it is not always clear which physical mechanisms determine the degradation of one or another type of LDs. More than ten such mechanisms are considered in review [9], while the recent theoretical model of COD of single-transverse-mode LDs developed in [11] takes into account six heat release

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mechanisms. It is obvious that each of these mechanisms also has some influence on the slow aging process. Unfortunately, the parameters characterising the contribution of each of the mechanisms to the degradation process cannot always be determined.

The reliability of a particular batch of LDs depends not only on their design [substrate, heteroepitaxial structure (HES), active waveguide, cavity, electric contacts, heat sink, assembling features, etc.], but also on the accuracy of the fabrication process. The LD fabrication process includes tens of technological steps. A deviation from the optimal regime at each of the steps may cause defects affecting the device reliability, including defects that can be annealed in the process of operation. In the case of an imperfect technology, a spread in the lifetime characteristics of similar LDs from different batches is unavoidable. Different batches of LDs of one and the same type may degrade due to different dominant physical mechanisms. All the above is also true for SLDs. In fact, conventional SLDs differ from conventional LDs only by extremely low reflection coefficients at the facets of the active channel. Comparison of SLDs and LDs that have identical configurations, are based on identical HESs, and have the same output powers shows that the main difference between them consists in the distribution of light fluxes and concentrations of nonequilibrium carriers along the active channel axis, the average concentration being much higher in SLDs. These differences may affect the degradation processes.

Aging of single-transverse-mode SLDs of the near-IR spectral region (800–900 nm) made of a bulk double-sided separate confinement (GaAl)As heterostructure was studied in [12, 13]. It was shown that, at a moderate (5–10 mW) output cw power, the lifetime of these SLDs at room temperature may exceed 10^5 h. As far as we know, there are no publications devoted to the reliability of broadband quantum-well SLDs of this spectral region.

In the present work, we do not try to identify the physical mechanisms responsible for the degradation of studied SLDs. We solve a more modest but practically important problem, namely, we experimentally study the variations in the power and spectral characteristics of these devices in the process of long operation and develop a method for estimating their expected lifetime.

2. Method of life tests of active elements of SLD modules

The output characteristics of SLDs for OCT systems must satisfy a number of specific requirements. SLDs are usually used under the conditions when the active element temperature is stabilised at 25 °C. Their working current is limited from above, while the output optical power is strictly limited from both above and below. Taking into account the two-peak shape of the spectrum, limitations are imposed on the median wavelength λ from above and below, on the spectral flatness SF and residual Fabry–Perot modulation depth (ripple) from above, and on $\Delta\lambda$ (FWHM) from below. For modules of the SLD-37 series, which are most frequently used in commercial OCT systems, the minimum $\Delta\lambda$ is 45 nm. The fulfilment of all these conditions is a difficult technical problem.

Especially difficult is to keep the minimum $\Delta\lambda$ because the spectral shape strongly depends on the injection current (Fig. 1a). At low currents, superluminescence is determined by quantum transitions from the ground state. In this case, the spectrum has a bell-like shape. An increase in the current

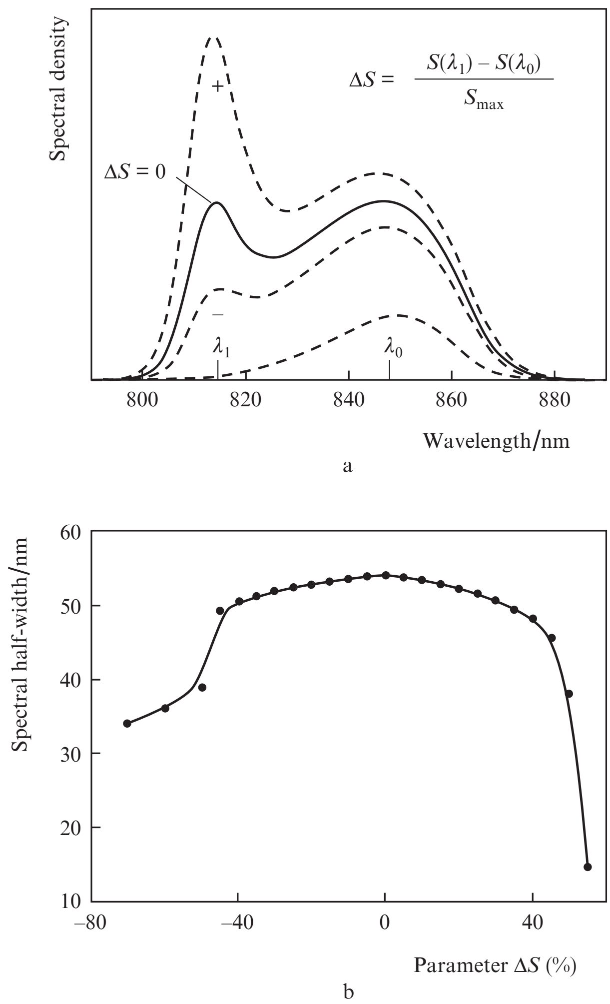


Figure 1. Variations in the SLD spectrum with injection current (a) and dependence of the spectral half-width on the ΔS parameter (b).

leads to the appearance of a short-wavelength peak caused by quantum transitions from the excited subband. At a current I_0, the spectral peaks $S(\lambda_1)$ and $S(\lambda_2)$ become equal ($\Delta S = 0$) and $\Delta\lambda$ reaches its maximum. With a further increase in the current, the short-wavelength peak becomes dominant. As was mentioned above, SLD modules in OCT systems operate just at the point $I = I_0$. Figure 1b shows a typical dependence of $\Delta\lambda$ on the degree of spectrum nonuniformity ΔS. It is obvious that, using such SLDs for a long time at a fixed current and temperature, one should expect a change not only in the output power, but also in the shape of the radiation spectrum. In the present work, we study these processes as applied to active elements of SLD modules, namely, to semiconductor diode crystals mounted on copper heat sinks (SLD chips). A sufficiently high reliability of the design and assembling technology of the modules is confirmed by a long-term production of SLD modules of other types.

For testing, active elements were placed into hermetic cells in a special eight-position mount, which included holders mounted on OTT-23-1.3-28 Peltier microcoolers, a system of pressure contacts, and photodiode arrays to measure the output optical power. The temperature of the active elements was stabilised with an accuracy of 0.1 °C; to stabilise required injection currents and measure photocurrents, we used eight-channel PILOT-4 controllers. They stabilise prescribed injection currents in the ACC regime with an accuracy of 0.1 mA and photocurrents in the APC regime with an accuracy of 1 μA, which corresponds to the relative power measurement accuracy of about 0.01 %. Readings were taken automatically once a day.

Each processed heteroepitaxial structure (PEHS), namely, an EHS fragment gone through the fabrication procedure, contains hundreds of future active elements with formed active channels with lateral optical and electrical confinement and with contacts from the N and P sides. The final operations of production of active elements are cleaving of a PEHS into crystals, antireflection coating of faces, and mounting of crystals on copper heat sinks. As a rule, active elements produced from one PEHS have similar output and lifetime characteristics.

From each PEHS, we prepared a test batch of SLDs with active channels of different lengths. After measuring their characteristics and choosing the optimal configuration corresponding to some or other technical requirements, we performed preliminary burn-in tests of a batch consisting of 16 samples of the chosen configuration under the working current I_0 in the ACC regime for 120–240 h. After these tests, we measured the output spectral characteristics again. This procedure allows us to discard samples with fatal technological defects, which are usually burned in for the first day ('infant mortality'), to determine the tendency of changes in the output characteristics of SLDs in the course of their operation, and to select 8 typical samples for long-term life tests.

Figure 2 illustrates the behaviour of the output power observed in the process of preliminary tests of samples made of different PEHSs. Samples of type I show a rapid monotonic decay of the output power (more than 1 % per day). They were not subjected to long-term tests, and the corresponding PEHSs were rejected. The power of type II samples demonstrates a slowing decrease, whose rate to the end of the preliminary test does not exceed 0.2 %–0.4 % per day. Type III samples are characterised by a slow aging from the very beginning of the tests, while the power of type IV samples increases at the beginning of the test and than, after reaching a maximum, slowly decreases. Thus, to the end of preliminary tests, the samples of types II–IV behave almost identically. The power of type V samples demonstrates an increase that slows down but does not cease to the end of the test. Running ahead, note that this process continues to the end of long-term life tests. The output spectra of the samples of types II and III showed a decrease in the intensity of the short-wavelength maximum ($\Delta S < 0$) to the end of tests. The spectra of the samples of types IV and V were observed to change their shape with enhancement of the short-wavelength ($\Delta S > 0$) or long-wavelength ($\Delta S < 0$) peaks depending on the PEHS.

The tendencies described point to the existence of at least three physical mechanisms affecting the change in the output characteristics of considered SLDs during their exploitation. First, it is a common aging related to the appearance of new nonradiative recombination centres, which results in a decrease in the concentration of nonequilibrium carriers at a given injection current and in the output power, as well as in the height of the short-wavelength maximum in the emission spectrum ($\Delta S < 0$). The increase in the output power can be caused both by defect annealing leading to a decrease in the nonradiative recombination rate, to an increase in the concentration of nonequilibrium carriers, and to the corresponding growth of the short-wavelength spectral maximum ($\Delta S > 0$), and by defect annealing decreasing the optical losses in the active channel, which, together with an increase in the effective optical gain, decreases the concentration of nonequilibrium carriers and the height of the short-wavelength spectral peak ($\Delta S < 0$). Moreover, investigations showed that, in the case of testing identical SLD samples at different temperatures, the dominant physical mechanisms changing the output characteristics may be different. As an example, Fig. 3 presents the chronograms of the output power of preliminarily tested iden-

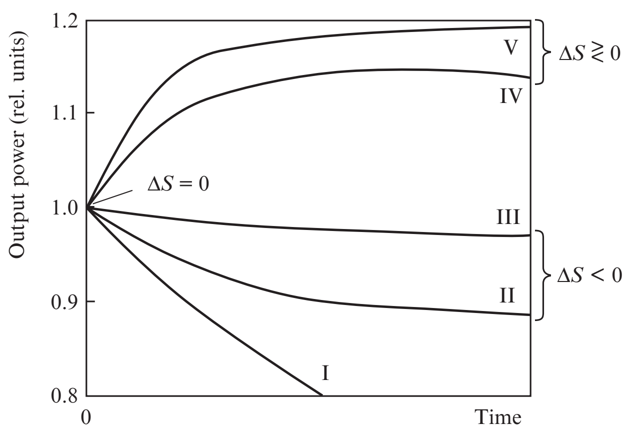


Figure 2. Chronograms of the output power for SLDs made of different PEHSs in the course of preliminary life tests in the ACC regime.

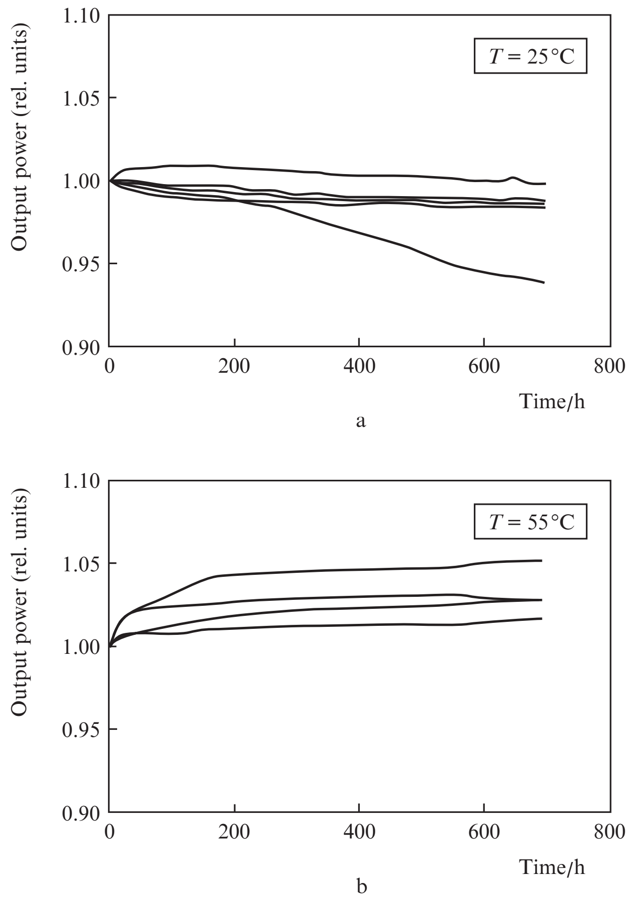


Figure 3. Chronograms of the output optical power $P_{FS}(t)$ of one-type SLDs made of the same PEHS in the ACC regime at 25 and 55 °C.

Table 1. Parameters of a S009-129R SLD measured in the course of life tests (database fragment). Test conditions: ACC regime, 119 mA, 25 °C.

Time/h	Measurement date	I/mA	U_0/V	P_{FS}/mW	P_{SM}/mW	λ/nm	$\Delta\lambda$/nm	SF (%)	ΔS (%)	Rip (%)	τ_p/h
0	22.01.10	119	1.777	8.90	4.78	841.4	45.8	14.5	0	0.3	
1000	07.03.10	119	1.776	8.11	4.39	841.6	45.5	14.5	–5	0.3	7100
1001	07.03.10	120	1.777	8.31	4.50	841.5	45.8	13.5	0	0.3	
2000	24.04.10	119	1.766	7.41	4.05	842.5	44.9	19.0	–13	0.3	5700
2001	24.04.10	123	1.771	8.29	4.57	841.7	45.9	15.0	0	0.3	
3000	05.06.10	119	1.768	6.93	3.77	843.0	44.7	21.5	–18	0.4	13200
3001	05.06.10	125	1.777	8.18	4.53	841.8	46.1	14.5	0	0.4	

tically designed SLDs made of the same PEHS in the process of subsequent testing in the ACC regime at temperatures of 25 and 55 °C with the injection current corresponding to equalised spectral maxima ($\Delta S = 0$) at 25 °C. These SLDs are aging at room temperature (Fig. 3a) and 'become younger', i.e., exhibit an increase in the power with time, at the higher temperature (Fig. 3b).

The presented data indicate that the conventional methods of determination of the lifetime of LDs [14] cannot be used for considered SLDs. In these methods, a device is considered as failed if its output power decreases by 50 % in the case of ACC regime or if its injection current increases by 50 % in the case of the APC regime. In addition, it is assumed that the slow degradation at different temperatures is determined by one physical mechanism, namely, by defect activation, and that the lifetime τ obeys the Arrhenius relation

$$\frac{\tau(T_1)}{\tau(T_2)} = \exp\left[\frac{E_a}{k}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right], \tag{1}$$

where T_1, T_2 are the working temperatures, k is the Boltzmann constant, and E_a is the activation energy equal to several tenths of an electron-volt for LDs. This approach allows one to perform accelerated life tests at higher temperatures and sufficiently correctly estimate the lifetime of highly reliable LDs, whose degradation at room temperature occurs very slowly. This method is also successfully used for SLDs of some types [15, 16].

Since this approach is unacceptable for our conditions, we restricted ourselves to the life tests of SLD chips at a temperature of 25 °C. Eight typical samples from each new PHES that passed the preliminary life test were then tested for 3000 h in the ACC regime at the current I_0. Before the test, we measured the main parameters of SLDs, namely, working voltage U_0, free-space output optical power P_{FS}, output optical power coupled into a single-mode optical fibre with a standard end microlens P_{SM}, median wavelength λ, spectral half-width $\Delta\lambda$, spectral flatness SF, and residual Fabry–Perot modulation depth Rip. During the test, these measurements were repeated after 1000, 2000, and 3000 h at the same injection current. In addition, we determined a new value of I_0 and measured new values of the above parameters. We also measured ΔS and calculated the lifetime τ_p (the method of its determination is discussed below). The fragment of the database presented in Table 1 contains the parameters of one active element measured in the course of testing. Lines 1001, 2001, and 3001 show the results measured at new currents I_0.

In the future, according to recommendations given in [14], it is proposed to perform life tests of PHESs at a higher temperature in parallel with incoming inspection.

3. Results of life tests

During two years, such life tests were performed for 27 batches of samples made of PHESs obtained from heterostructures grown in six similar processes of metallorganic chemical vapour deposition (MOCVD). Figure 4 presents typical time dependences $P_{FS}(t)$, $\Delta S(t)$, and $I_0(t)$. The shape of dependences shown in Fig. 4a is characteristic for SLD samples of types II–IV. In the course of their aging, one observes a slow decrease in the output power and a reduction of the short-wavelength spectral peak ($\Delta S < 0$). The output power of type V samples increases up to the end of testing. This behaviour cannot be called anomalous since it was typical for 14 out of 27 batches of samples. With increasing time of operation, we observed continuous deformation of the spectral shape with enhancement of either the long- or short-wavelength (Fig. 4b) peaks.

After smoothing and linear extrapolation of dependences $P_{FS}(t)$, we estimated the power lifetime τ_p of each sample. For the samples whose output power monotonically decreased with time, we used the common failure criterion

$$P_{FS}(\tau_p) = \frac{1}{2} P_{FS}(0). \tag{2}$$

For the sample demonstrating an increase in the output power during the test, we introduced the 'symmetric' failure criterion

$$P_{FS}(\tau_p) = \frac{3}{2} P_{FS}(0). \tag{3}$$

This approach is justified by the fact that all the specifications for modules of the SLD-37 series used in OCT contain limitations on the output power from above related, in particular, to laser safety measures. It should be noted that the lifetime τ_p determined by this method is only an estimate. Sooner or later, annealing of any defects must stop. After this, the output power decreases with a rate determined by the dominant aging mechanism. In other words, the dependence $P_{FS}(t)$ may pass through a maximum at $P_{FS} < 1.5\,P_{FS}(0)$. The real lifetime of a device can be both longer and shorter of the time estimated by linear extrapolation at t = 3000 h. Two batches of type V samples after operation for 3000 h and measurement of parameters, were subjected to a further life test. At the time of submission of this paper, these samples have worked for more than 7000 h (almost a year), and their output power continues to increase. Table 2 shows the average lifetimes τ_p determined by criterion (3) at t = 2000, 3000, 5000, and 7000 h.

Most probably, the lifetime τ_p determined at t = 3000 h is a reliable estimate from below. Tests are continuing.

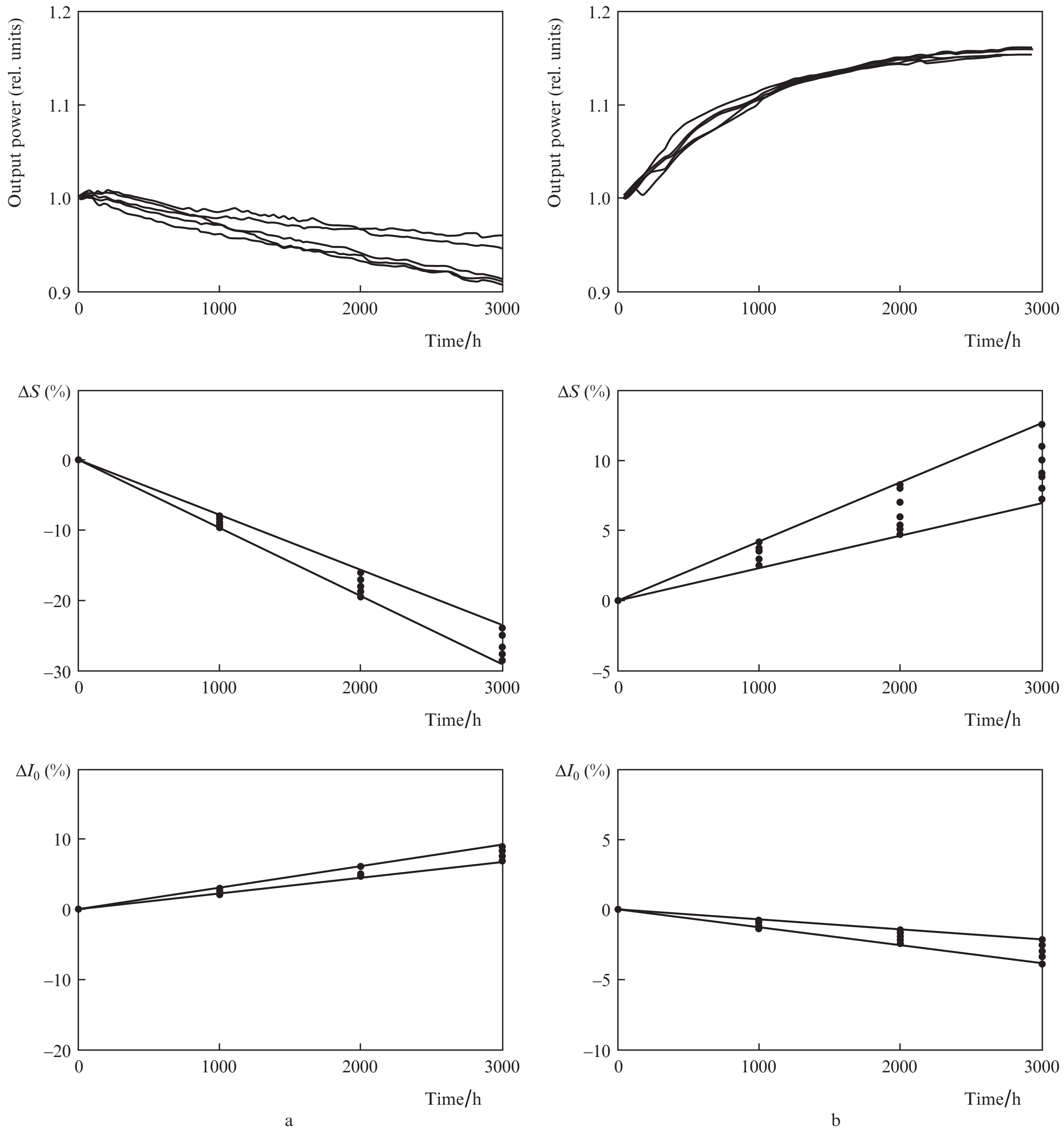


Figure 4. Typical dependences $P_{FS}(t)$, $\Delta S(t)$, and $\Delta I_0(t)$ for SLDs of types II–IV (a) and V (b).

Table 2. Average power lifetimes for type V samples made of two PEHSs determined by linear approximation of $P_{FS}(t)$ at $t = 2000$, 3000, 5000, and 7000 h.

PEHS number	τ_p/h estimated at testing for			
	2000 h	3000 h	5000 h	7000 h
V-1387	20000	24500	60000	94400
V-1514	38000	58000	310000	351000

The situation with the spectral lifetime is more complicated. There exist no general commonly accepted criteria of its determinations. The dependence $\Delta\lambda(\Delta S)$ shown in Fig. 1b suggests that it is reasonable to use the failure criterion

$$|\Delta S(\tau_s)| = 40\%. \tag{4}$$

Indeed, when ΔS exceeds 40%, the parameter $\Delta\lambda$ begins to decrease rapidly. In the case of using this criterion, the spectral aging turns out to be the main factor limiting the SLD lifetime. This is illustrated by the histogram shown in Fig. 5a. For 22 out of 27 studied PEHSs, the average spectral lifetime is smaller than the power lifetime determined by criteria (2) and (3). For most of them, τ_p exceeds τ_s by several times.

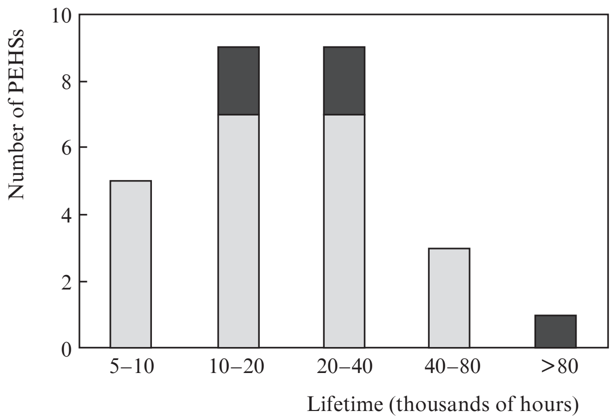
In parallel with life tests in the ACC regime, eight samples out of each of four PEHSs were subjected to life tests in the APC regime for 3000 h. Comparative analysis of the results showed that the average spectral lifetime in the latter case is approximately twofold longer. The average lifetimes τ_s were 7400, 12700, 22600, and 31300 h for the ACC regime and 16200, 22400, 46100, and 55800 h for the APC regime. However, in the APC regime, the spectral deformation also remains the dominant factor limiting the lifetime.

For practical applications in which it is possible to adjust the injection current in the process of SLD exploitation, the spectral lifetime can be considerably increased. Comparing the dependences $P_{\rm FS}(t)$, $\Delta S(t)$, and $I_0(t)$ shown in Fig. 4, one can see that a long operation in the ACC regime leads to a considerably weaker relative changes in the output power and working current than in the spectral shape. The lifetime can be increased by changing I_0 for a new one corresponding to the maximum spectral width ($\Delta S = 0$) after each particular time of continuous operation (for example, 5000 or 10 000 h), or by performing such adjustment automatically. As was noted above, in all specifications of considered SLDs, the current I_0 is limited from above. Reliable statistics shows that the limiting value of I_0 for overwhelming majority of samples after preliminary tests exceeds the real value by 20%–40%. Based on this, we can introduce such a spectral failure criterion as the impossibility to equalise the spectral maxima (to obtain $\Delta S =$ 0) when the working current changes within ±20%. In other words,

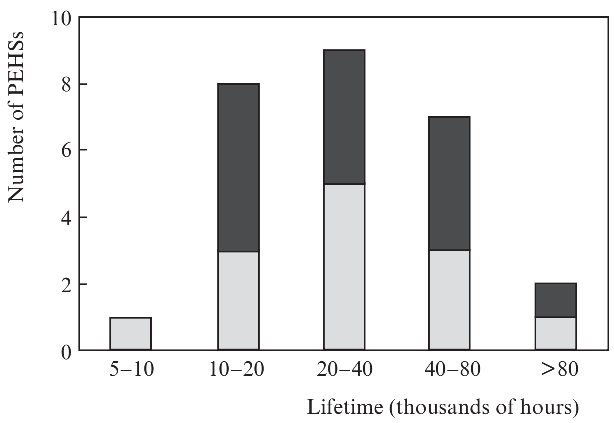
$$|\Delta I_0(\tau_s)| = 20\%. \tag{5}$$

Figure 5b presents the histogram of the expected lifetime of SLDs made of the same PEHSs plotted using criterion (5). Comparison of the histograms in Figs 5a and 5b shows that the use of this criterion allows one to use SLDs more efficiently, i.e., to increase noticeably the average lifetime, in particular, to decrease considerably the percentage of short-lived samples with a service life below 10000 h [from 18.5% (5 samples out of 27) to 3.7% (1 out of 27)] and increase the percentage of long-lived samples with $\tau > 40000$ [from 14.8% (4 out of 27) to 33% (9 out of 27)]. In addition, the lifetimes τ_s and τ_p in this case become closer to each other. While the ratio of PEHSs with $\tau_s < \tau_p$ to PEHSs with $\tau_s > \tau_p$ in the case of criterion (4) is 22 : 5, this ratio in the case of criterion (5) is 13 : 14.

The obtained data allow us to estimate the lifetime dispersion of the samples made of different PEHSs. Typical rms deviations of τ from its average values amounting to approximately 15, 30, and 50 thousands of hours were found to be about 3, 8 and 20 thousands of hours, respectively.



a



b

Figure 5. Histograms of the expected lifetime of SLDs made of different PEHSs ($\tau = \min[\tau_p, \tau_s]$) plotted for τ_s determined using criteria (4) (a) and (5) (b). Light and dark rectangles correspond to $\tau_s < \tau_p$ and $\tau_s > \tau_p$, respectively.

4. Conclusions

Our investigations showed that the most part of devices that successfully passed the preliminary life test have expected lifetime exceeding 10^4 h. It is experimentally demonstrated that, in the case of stable operation conditions in the ACC and APC regimes, the spectral aging (deformation of the output radiation spectrum) is the main process limiting the SLD lifetime. This lifetime can be considerably increased when the device operation conditions allow casual or automatic adjustment of the injection current in the ACC regime or of the output power in the APC regime. The used method of life tests allows one to select PEHSs with respect to the expected lifetime of SLDs made of these PEHSs depending on the SLD operation regime.

The results of this study facilitate the competitiveness of light-emitting modules of the SLD-37 series.

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