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Single-transverse-mode near-IR superluminescent diodes with cw output power up to 100 mW

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***Abstract.* A series of light-emitting modules based on single-mode quantum-well superluminescent diodes with centre emission wavelengths of about 790, 840, 960 and 1060 nm and a cw output power up to 100 mW in free space is developed. A sufficiently long service life of these devices is demonstrated.**

Keywords: *nanoheterostructure, quantum-well superluminescent diode.*

1. Introduction

A key parameter for many practical applications of superluminescent diodes (SLDs) is output optical power. In most cases, one prefers light-emitting modules based on single spatial mode SLDs, whose divergence is close to the diffraction limit.

At present, the optoelectronic market offers a great variety of single-transverse-mode laser diodes (LDs) of different spectral regions with hundred-milliwatt cw output powers. The powers of commercially available SLDs are much more moderate. This relates to a lower external quantum efficiency of SLDs, as well as to the fact that, due to a higher concentration of nonequilibrium charge carriers in working regimes, SLDs have lower thresholds of catastrophic optical damage (COD), while their ageing processes are faster than in LDs. The number of publications devoted to improvement of LD and SLD characteristics differs significatly. Nevertheless, during the last two decades, single-mode IR SLDs with a cw output power exceeding 100 mW were studied in a fair amount of experimental works (see, for example, [1 – 6]). The problem of reliability of these devices usually was not considered. To date, the mentioned level of power was achieved only for commercial SLD modules with a wavelength of about 1300 nm (from DenseLight). As to SLDs operating in the nearest IR range 750 – 1100 nm, despite a higher efficiency, the output power of such commercial SLDs does not exceed 60 mW (Superlum Diodes Ltd., EXALOS, InPhenix, DenseLight, Optoenergy Inc., etc.).

An obvious way to increase the output power is to use SLDs with a wide multimode active channel. However, their divergence in the p – n junction plane considerably exceeds the diffraction limit [7], which in many cases restricts their practical application. The same can be said about integrated SDLs [8]. A comprehensive solution to the problem is to use MOPA systems, in which the master oscillators are SLDs and the power amplifiers are semiconductor optical amplifiers (SOAs) with tapered channels, whose divergence is close to the diffraction limit. For example, Toptica and Sacher Lasertechnik produce a large series of such SOAs for various spectral regions. At an input signal power of 5 – 50 mW, their output cw power amounts to 3 W. These MOPA systems, as a rule, contain focusing and collimating optics, as well as an optical isolator between the SLD and SOA. These systems represent a separate class of devices, relatively large-sized and expensive. As far as we know, experiments on creation of such systems in an integral design without optical isolation [9] yielded no practical results.

A rather interesting design is used in SLDs with a multimode interferometer as the active channel [10, 11]. These SLDs have a diffraction-limited divergence and, at the same time, allow one to considerably increase the output power and decrease the current load due to a larger volume of the active channel compared to traditional 'narrow' SLDs. Unfortunately, this design does not solve the problem of COD related to destruction of faces.

In the present work, we study traditionally designed IR SLDs. They were made using four high-quality semiconductor nanoheterostructures, which were grown by MOCVD, as well as an optimised technology of formation of active channels and ionic cleaning of faces prior to deposition of antireflection coating [12]. This allowed us to increase the external efficiency of SLDs and their COD thresholds. Miniature light emitting modules based on the developed SLDs have demonstrated a rather high reliability at a cw output optical power up to 100 mW.

2. Experimental samples and their characteristics

The semiconductor nanoheterostructures with quantum-well active layers and separate confinement used for the studied SLDs were specially grown by MOS-hydride epitaxy in SIGMOS and AIXTRON reactors. The main structural parameters of these nanoheterostructures are listed in Table 1. All experimental samples had identical design. The straight active channel of SLDs was a ridge waveguide 1500 μm long and 4 μm wide inclined at an angle of 7° with respect to the normal to the antireflection-coated crystal faces.

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Table 1. Main structural parameters and typical technical characteristics of studied SLDs.

SLD type	Active layer composition and thickness/nm	Waveguiding layer composition and thickness/µm	$I_{\rm SLD}$/mA	$\lambda_{\rm m}$/nm	$\Delta\lambda$/nm	$R_{\rm IFP}$ (%)	COD threshold/mW A^{-1}
I	GaAs, 3.5	$Al_xGa_{1-x}As$ (x = 0.25–0.5), 0.3	300	795	16	2–3	200/700
II	GaAs, 9.0	$Al_{0.3}Ga_{0.7}As$, 0.25	360	840	25	3–4	220/700
III	$In_{0.2}Ga_{0.8}As$, 6.0	$Al_xGa_{1-x}As$ (x = 0–0.5), 0.4	370	960	50	4–6	220/800
IV	$In_{0.35}Ga_{0.65}As$, 2 layers 7.0 nm each	$Al_{0.25}Ga_{0.75}As$, 0.5	425	1060	40	5–7	Overheating without COD

Note: $I_{\rm SLD}$ is the injection current corresponding to the output power of 100 mW at 25 °C and the presented spectral characteristics; $\lambda_{\rm m}$ is the median wavelength; $\Delta\lambda$ is the spectral half-width; and $R_{\rm IFP}$ is the depth of residual modulation of the spectrum due to Fabry–Perot modes.

As is known, in quantum-well SLDs with active layers several nanometers thick, at high concentrations of nonequilibrium charge carriers, not only the ground but also the excited subbands of the energy spectrum are filled. As a result, the amplified spontaneous emission spectrum has a typical double-hump shape. This shape was not observed for the studied SLDs. Up to an injection current density of $\sim 10^4$ A cm^{-2}, their spectra had a bell-like quasi-Gaussian shape [13], which testifies that the superluminescence is formed only by the quantum transitions from the ground subband. Filling of excited subbands in this case is hindered due to a high quantum efficiency and a large length of the active channel (high single-pass optical gain), which lead to an efficient drop in inversion.

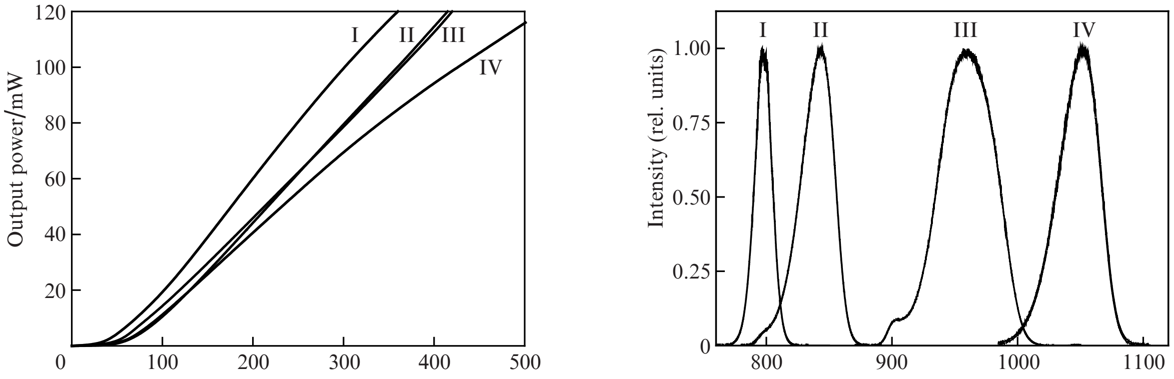
Table 1 also lists the main spectral parameters of the studied SLDs in the operation regimes corresponding to a cw output power of 100 mW. The COD threshold, which is related, as rule, to destruction of faces, was 200–220 mW for SLDs of types I–III. For the samples of type IV, we observed no COD, but the output power thermally saturated with increasing injection current.

Typical light–current characteristics and emission spectra of the studied SLDs are presented in Fig. 1. A typical far-field radiation is shown in Fig. 2. This figure presents the output beam cross section and the angular dependences of radiation intensity in the planes perpendicular and parallel to heterolayers. As was noted in the Introduction, the obtained radiation powers are not record-breaking for near-IR SLDs. The main achievement of the present work is the demonstration of a sufficiently high reliability of the developed devices in the considered operation regimes. Figure 3 presents the chronograms of preliminary lifetime tests of SLDs of types II and III at an injection current of 400 mA. Extrapolation of the presented dependences allows us to estimate the median lifetimes of these SLDs to be about 15000 and 11000 h, respectively. Similar tests are being performed at the moment for SLDs of types I and IV. According to preliminary estimates, their median lifetimes will also exceed 10000 h.

3. Miniature light-emitting modules

As a result of the performed research, we developed light-emitting modules in standard TOW and TO-9 packages. Modules of the first type contain, in addition to a SLD, a thermoelectric microcooler (TEMC), a thermistor and a monitor photodiode, which makes it possible to use standard electronic controllers for temperature stabilisation and automatic output power control. The chronograms in Fig. 4 illustrates levelling off of the TEMC current in the case of temperature stabilization of SLDs at 25 °C for injection currents of 300 and 400 mA and different environmental temperatures. These dependences show that, at least at environmental temperatures up to 55 °C, these modules can operate with the output characteristics shown in Fig. 1. Obviously, the use of a larger package and a more efficient TEMC will allow one to considerably extend the range of allowable working temperatures.

Modules of the second type contain only an SLD and a monitor photodiode. In the case of using an external temperature stabilisation system, they also operate with the above-presented output characteristics. If they are used being mounted on a rather heavy heat sink, their output optical characteristics change with environmental temperature, i.e., in the automatic power control regime the central wavelength and the spectral width increase with increasing temperature. These changes are illustrated in Fig. 5 on the example of mod-



a b

Figure 1. (a) Current–voltage characteristics of the studied SLDs at 25 °C and (b) their emission spectra at an output power of 100 mW.

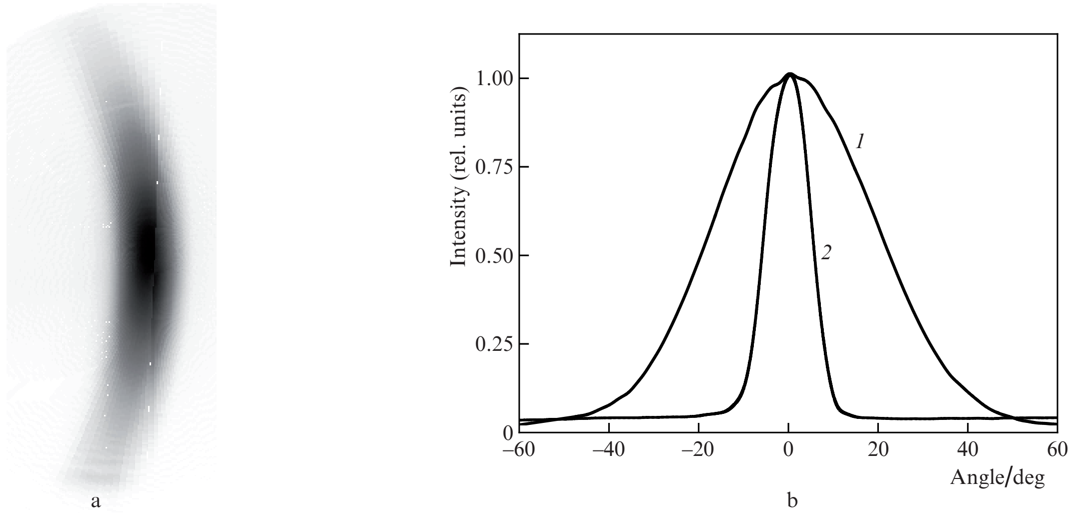


Figure 2. Typical far-field radiation: (a) beam cross section and (b) intensity distribution in the planes (*1*) perpendicular and (*2*) parallel to heterolayers.

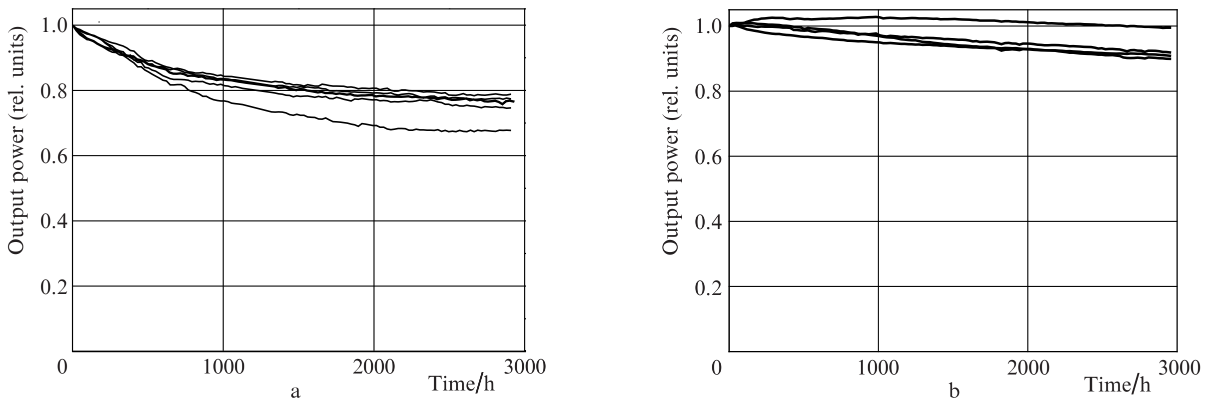


Figure 3. Chronograms of preliminary lifetime tests of SLDs of types (a) II and (b) III at an injection current of 400 mA.

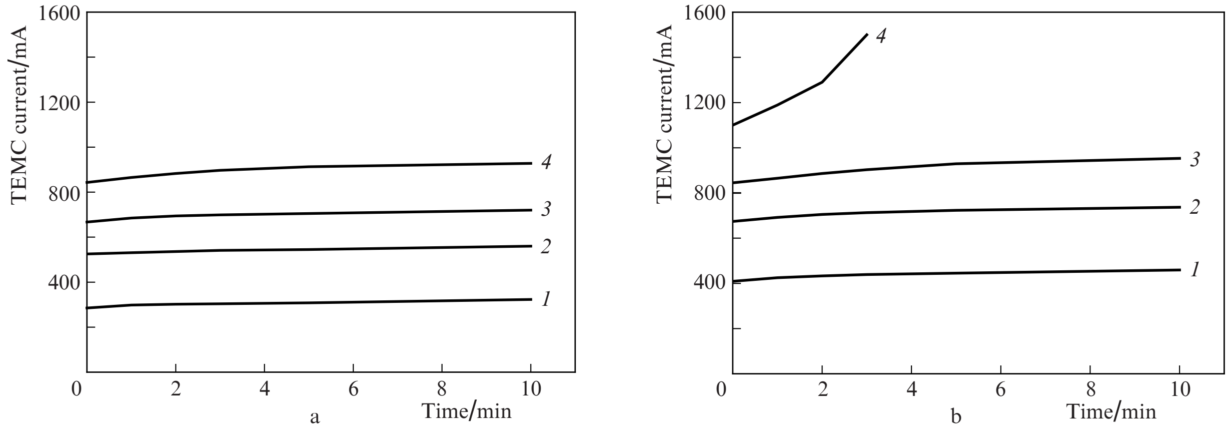


Figure 4. Transient processes in a TEMC. Injection currents (a) 300 and (b) 400 mA; temperature stabilisation at 25 °C; environmental temperatures (*1*) 25, (*2*) 45, (*3*) 55 and (*4*) 65 °C.

ules based on SLDs of type II in TO-9 packages. It is these devices that are commercially produced as the first fruit (model SLD 340-UHP).

Thus, we studied prototypes of miniature single-spatial-mode SLD modules with centre wavelengths 790, 840, 960 and 1060 nm. It is shown that, at a cw output optical power of 100 mW, their lifetime exceeds 10000 h. These modules surpass the commercially available analogues in output power approximately twofold.

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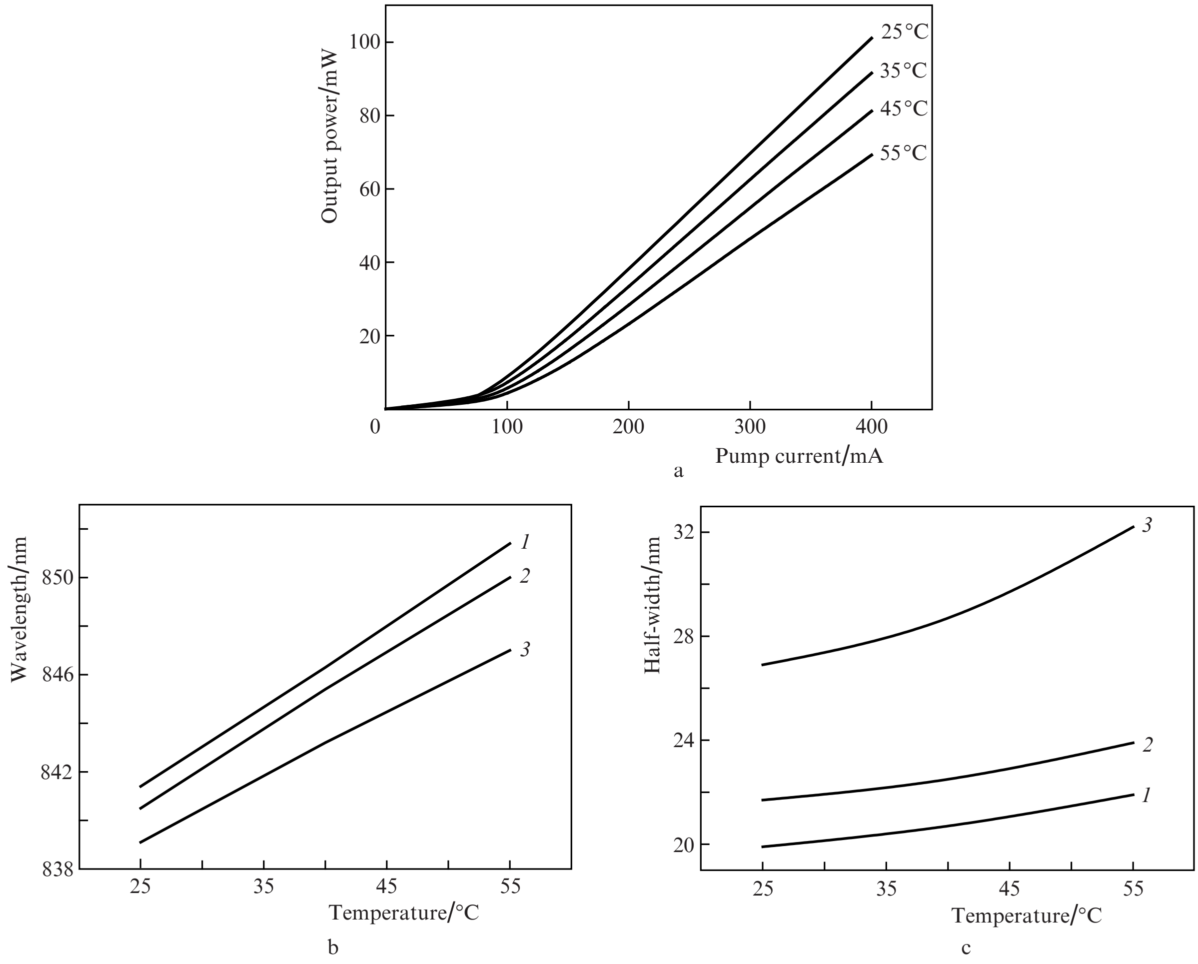

Figure 5. (a) Light–current characteristics at different temperatures and temperature dependences of (b) the centre wavelength and (c) spectral width at output powers of (*1*) 5, (*2*) 10 and (*3*) 50 mW for an SLD of type II in TO-9 package (heat sink without temperature stabilisation).

sov with their colleagues for performing growth of nanoheterostructures and their post-growth treatment.

References

1. Goldberg L., Mehuys D. *Electron. Lett.*, **30** (20), 1682 (1994).
2. Takayama T., Imafuji O., Kouchi Y., Yuri M., Yoshikava A., Itoh K. *IEEE J. Quantum Electron.*, **32** (11), 1981 (1996).
3. Konoplev O.A., Park S., Saini S.S., Merrit S.A., Hu Y., Luciani V., Heim P.J.S., Enk R., Bowler D. *Proc. SPIE Int. Soc. Opt. Eng.*, **5739**, 66 (2005).
4. Sugo M., Yoshimura R., Shibata Y. *Electron. Lett.*, **42** (21), 1245 (2006).
5. Yamatoya T., Mori S., Koyama F., Iga K. *Jpn. J. Appl. Phys.*, **38** (Part 1, 9A), 5121 (1999).
6. Zhang Z.Y., Hogg R.A., Jin P., Choi T.L., Xu B., Wang Z.G. *IEEE Photonics Technol. Lett.*, **20** (10), 782 (2008).
7. Andreeva E.V., Batrak D.V., Bogatov A.P., Lapin P.I., Prokhorov V.V., Yakubovich S.D. *Kvantovaya Elektron.*, **37** (11), 996 (2007) [*Quantum Electron.*, **37** (11), 996 (2007)].
8. Causa F., Burrow L. *IEEE J. Quantum Electron.*, **43** (11), 1055 (2007).
9. Du G., Xu C., Liu Y., Zhao Y., Wang H. *IEEE J. Quantum Electron.*, **39** (1), 149 (2003).
10. Zang Z., Minato T., Navaretti P., Hinokuma Y., Duelk M., Velez C., Hamamoto K. *IEEE Photonics Techol. Lett.*, **22** (10), 721 (2010).
11. Soldano L.B., Penning E.C.M. *J. Lightwave Technol.*, **13** (4), 615 (1995).
12. Lobintsov A.A., Uspenskii M.B., Shishkin V.A., Shramenko M.V., Yakubovich S.D. *Kvantovaya Elektron.*, **40** (4), 305 (2010) [*Quantum Electron.*, **40** (4), 305 (2010)].
13. Andreeva A.V., Il'chenko S.N., Kostin Yu.O., Ladugin M.A., Lapin P.I., Marmalyuk A.A., Yakubovich S.D. *Kvantovaya Elektron.*, **43** (8), 751 (2013) [*Quantum Electron.*, **43** (8), 751 (2013)].