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Highly reliable high-power superluminescent diodes with three single-mode active channels

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Abstract. **We report superluminescent diodes (SLDs) with three ridged active channels, each having a width of 3.5 μm, based on one 'bulk' and two quantum-well heterostructures. At a cw output power greater than 100 mW, the emission spectra of these SLDs possess a quasi-Gaussian shape with centre wavelengths near 840, 860 and 1060 nm and widths about 15, 25 and 40 nm, respectively. In the above operating conditions, the median service life of the SLDs amounted to approximately 50000, 25000 and more than 60000 h, respectively.**

Keywords: *superluminescent diode (SLD), semiconductor nanoheterostructure.*

1. Introduction

Solid-state lighting has already made a tremendous progress in everyday life of modern people. The dominant role in this technology is played by the semiconductor light-emitting diodes (LEDs) [1]. At the same time, in some practical applications (microscopy, machine vision, portable projectors, etc., see, e.g., [2 – 5]) the brightness of LED-based light sources is insufficient, and the use of laser diodes (LDs) is hampered by the interference phenomena, caused by high coherence of radiation. The problem can be solved by means of superluminescent diodes (SLDs), the radiation of which approaches that of laser diodes in brightness and that of LEDs in the degree of coherence. In conventional SLDs with a spatially single-mode active channel having a width on the order of a few micrometres, the value of the cw output optical power typically does not exceed a few tens of milliwatts. A dramatic increase in the output optical power is possible by using MOPA systems with SLDs as master oscillators and high-power output semiconductor optical amplifiers (SOAs) with a tapered active channel. However, this significantly increases the overall dimensions and the cost of the light source. An intermediate solution of this problem is to increase the volume of the SLD active channel. In our paper [6] we have presented the results of studying high-power SLDs with a wavelength near 840 nm based on a (GaAl)As separate-confinement heterostructure, the active layer of which has a thickness of 14.5 nm. The active channel was a ridged multimode optical waveguide having a width of 25 μm. These SLDs provide an output optical power of more than 200 mW. Their essential drawback is the strong dependence of the emission spectrum shape on the injection current (later this drawback was eliminated at the expense of using analogous structures with active layers thinner than 10 nm). One more negative feature of these SLDs is the dependence of the shape of the directivity pattern on the pump level, which is due to the spatial mode multiplicity of the active channel. Fortunately, this dependence within wide limits does not affect the coefficient of radiation coupling (75%) into standard multimode optical fibres (MOFs) when use is made of an end-face cylindrical microlens. For this reason, the considered SLDs find application mainly in light-emitting modules with the light output through MOFs. A serious disadvantage, which has still not been overcome, is a rather modest service life of these devices, as small as nearly 5000 h. It is worth noting that SLDs of similar construction based on a similar heterostructure, but having a single-mode active channel with a width of 4 μm at the same density of the injection current, as a rule, have a service life of a few tens of thousands hours. This difference can be related to worse conditions of heat removal in 'wide' SLDs, when the semiconductor crystal is mounted on the heat-removing element with its P-side up.

In the present paper, we study the SLDs with three separate active channels each having a width of 3.5 μm. This design allows the service life of the device to be markedly increased at an output optical power exceeding 100 mW.

2. Experimental samples

We studied SLD samples of three types, having the same configuration and based on different double separate-confinement heterostructures (DSCHs), grown by MOCVD. Figure 1 shows microphotographs of one of the studied SLDs. Each sample had three straight parallel ridge-shaped active channels having the width 3.5 μm and the length 1600 μm. The non-injected gaps between the channels had a width of 6.5 μm. The thickness of the 'underetched' P-emitter, which determined the lateral optical confinement, amounted to nearly 0.3 μm. The axes of the channels had a slope of 7° with respect to the normal to the faces of the crystal, on which double-layer AR-coatings were deposited. The used DSCHs differed from each other by the thickness and composition of the waveguide and emitter layers. The SLDs of type I had a 'bulk' active layer. In the SLDs of types II and III, the active

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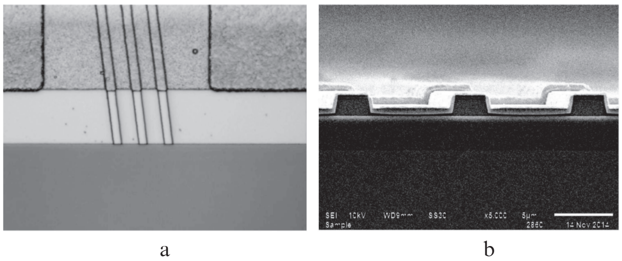


Figure 1. Microphotograph of the SLD sample: (a) top view (P-side); (b) end-face view.

layers were presented by one and two quantum wells (QWs), respectively. The specific features of the geometry and composition of heterolayers in the considered SLDs are summarised in Table 1.

Table 1. Composition and parameters of the SLD heterostructure.

SLD type	Composition and thickness of the active layer	Composition and thickness of the waveguide layer	Composition of the emitter layers
I	$Al_{0.03}Ga_{0.97}As$ ('bulk') 28 nm	$Al_{0.3}Ga_{0.7}As$ 0.26 μm	$Al_{0.5}Ga_{0.5}As$
II	$In_{0.05}Ga_{0.95}As$ (one QW) 6.0 nm	$Al_{0.3}Ga_{0.7}As$ 0.26 μm	$Al_{0.5}Ga_{0.5}As$
III	$In_{0.3}Ga_{0.7}As$ (two QWs) 2 × 8.0 nm	$Al_{0.25}Ga_{0.75}As$ 0.33 μm	$Al_{0.31}Ga_{0.69}As$

3. Basic physical characteristics of SLDs

We studied the power, spectral, spatial and service-life SLD characteristics in the regime of continuous injection under thermal stabilisation at a level of 25 °C. Figure 2 presents typical light–current characteristics of the SLD. Up to an injection current of about 800 mA, corresponding to an output power of about 120 mW, the light–current characteristics are linear and close to each other. At higher currents, the output power of quantum-well SLDs begins to be saturated. In the entire studied range of pump values, the emission spectra possessed the shape close to Gaussian, which is typical both for the 'bulk' SLDs and for the quantum-well ones with superthin active layers and great length of the active channel [7]. When the injection current increased, the width of the emission spectrum changed weakly in the samples of type I, and considerably increased in the samples of types II and III.

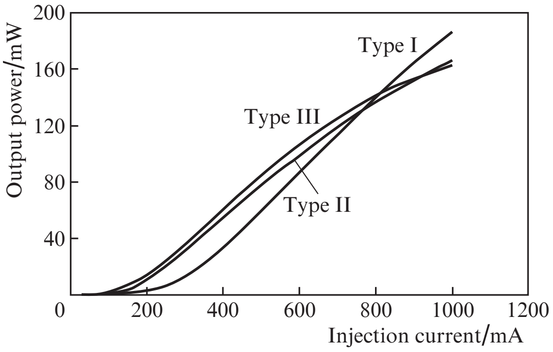


Figure 2. Light–current characteristics of the SLD in the continuous injection regime.

The typical emission spectra for the injection current 800 mA are presented in Fig. 3. The estimation of the coherence length using the formula $L_{coh} = 0.44\lambda^2/\Delta\lambda$, rigorously valid for spectral lines of Gaussian shape (λ is the centre wavelength and $\Delta\lambda$ is the spectral half-width) yields L_{coh} = 2.7, 13.0 and 12.3 μm for the SLDs of types I, II and III, respectively. The difference in the coherence length explains the qualitative difference between the radiation far-field patterns of type I samples and those of type II and III samples (Fig. 4). In the first case, one observes an interference pattern with a low visibility of fringes, much smaller than that observed in the integral sets of LDs [8]. In the second case, the directivity patterns have a smooth shape, characteristic for a single spatially single-mode SLD. Their quantitative difference in the divergence (approximately 10° × 40° for types I and II and 20° × 30° for type III) is due to the difference in the optical waveguide confinement (see Table 1) and in the radiation wavelengths. In the samples of types I and II the step of

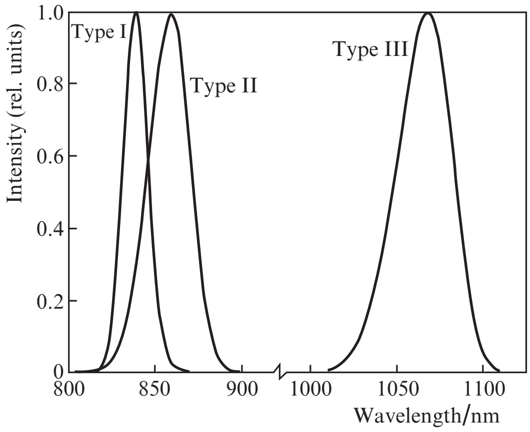


Figure 3. SLD emission spectra at the injection current 800 mA.

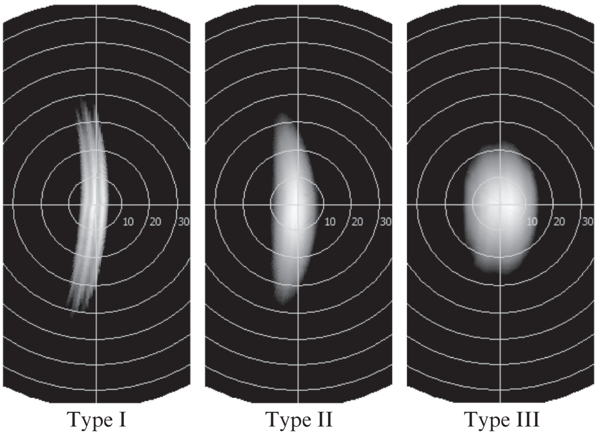
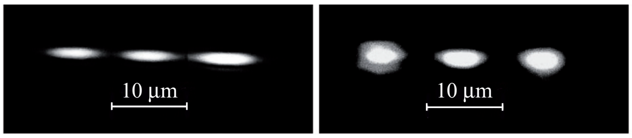


Figure 4. Far-field radiation of the SLD at the injection current 800 mA.

the refractive index at the boundary between the waveguide and emitter layers amounts to nearly 0.15, while in the sample of type III it is smaller than 0.1 [9]. As a result, the former ones have stronger transverse optical confinement and weaker lateral optical confinement than the latter ones, provided that the configuration of ridged waveguides is the same.

Figure 5 presents the near-field radiation for the samples of types II and III. The coefficient of radiation coupling into a standard step-index MOF with a core diameter 50 μm and a numerical aperture 0.22 through an end-face cylindrical microlens amounted to more than 80% for the SLDs of types I and II and nearly 60% for the SLD of type III. When using a gradient-index MOF with a core diameter 62.5 μm (the numerical aperture 0.27) the latter value increases to 75%.



Type II Type III

Figure 5. Near-field radiation of the SLDs of types II and III.

The preliminary lifetime tests of the SLD samples allow the estimation of their service life. For the diodes of types I and II at the injection current 800 mA the lifetime amounted to 50000 and 25000 h, respectively, and for the type III diode at the currents 800 and 100 mA – to 80000 and 60000 h, respectively. The presented values considerably exceed the service life of high-power (~100 mW) SLDs of the same spectral range, having one spatially single-mode active channel [10].

4. Conclusions

Based on the studies carried out, we have developed the prototypes of three light-emitting modules in Butterfly cases with the radiation output through MOFs, possessing the maximal output optical power of more than 100 mW. We have also developed and studied the prototypes of two light-emitting modules (based on the SLDs of types II and III) in the miniature TO-9 cases with the radiation output through an optical window, possessing the maximal output optical power of more than 120 mW. The former modules contain a thermoelectric microcooler with a thermistor for the SLD thermal stabilisation and a monitor photodiode, while the latter comprised only the SLD and the monitor photodiode. If necessary, the thermal stabilisation of the modules in the TO-9 cases can be provided using external devices.

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