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Two-section broadband superluminescent diodes

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Abstract. **Superluminescent diodes (SLDs) with two electrically isolated injection areas based on a single quantum-well GaAlAs/GaAs heterostructure operating at around 825 nm are studied experimentally. It is shown that varying the currents injected through the sections allows these SLDs to produce the cw output power from a few to nearly a hundred milliwatts without changing the spectral bandwidth (about 70 nm).**

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

1. Introduction

Shortly after the creation of semiconductor lasers, research on double-section ('tandem type') laser diodes (LDs) started [1, 2]. Published in many papers, the results of investigations of two- and multiple-section LDs showed that their performance characteristics are much more flexible than those of conventional single-section LDs. First of all, it concerns the emission dynamics (see, for example, [3]). Today, these optoelectronic devices find wide applications in many fields of engineering. Suffice it to say that in fibreoptic communication systems with wavelength-division multiplexing (WDM) the most part of transmitters includes multiple-section LDs.

As far as superluminescent diodes (SLDs) are concerned, they also often have a two-section design, one of the sections being only used as an absorber for suppressing optical feedback. First studied in [4], the SLD design with two isolated injection areas is not often used. It is however clear that this design provides another degree of freedom in controlling the output parameters of the emitter.

The last ten years have seen the ever-growing use of broadband SLDs based on quantum-well (QW) heterostructures with the emission spectrum defined by quantum transitions from two or more sub-bands of the energy spectrum. In this case the bandwidth and coherence degree of output light are strongly dependent on the SLD design and operation conditions. The typical examples demonstrating how the emission spectrum of such SLDs changes with the pump level at different lengths of the active region are given in [5, 6]. Light-emitting modules based on such SLDs are used mostly as light sources for various interferometric systems, in particular, for rapidly developing optical coherence tomography (OCT) [7]. As a rule, the main requirement for such sources is to provide the largest spectral bandwidth (the shortest coherence length).

However, in addition to the desirable large bandwidth, strict requirements are imposed on the output power. Meeting these demands at the same time often proves to be a complicated problem. Figure 1 shows typical dependences of half bandwidth $\Delta\lambda$ on the injection current I_{SLD} for two different SLD-modules of the SLD-37 series often used in OCT. It follows from the dependences $\Delta\lambda(I_{\mathrm{SLD}})$ that the near-maximum values of $\Delta\lambda$ can be achieved in a fairly narrow current range, which determines the output optical power P of this particular SLD. The power P can be varied slightly by changing the working temperature and adjusting the injection current correspondingly. However, this procedure is not always permitted by SLD-module operation conditions. The need to change P significantly, but keep $\Delta\lambda$ as large as possible prescribes almost a single solution in the case of homogeneous injection – fabrication of new SLD samples with a longer or shorter active channel length L_{a}. Nevertheless, with strict requirements for P and $\Delta\lambda$, a part of SLD samples proves to be unsuitable for a particular

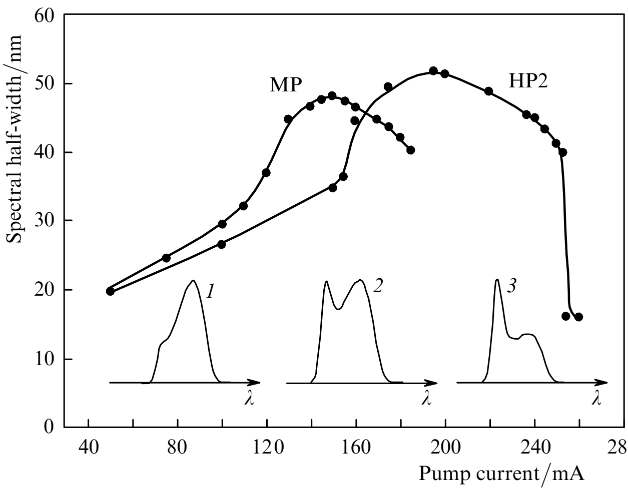

Figure 1. Typical dependences of the half bandwidth $\Delta\lambda$ (FWHM) on the injection current I_{SLD} for SLD-37 modules of the MP category ($P_{\mathrm{FS}} = 4 - 6$ mW) and HP2 category ($P_{\mathrm{FS}} = 20 - 30$ mW). The insets show typical shapes of the spectrum for a low pump level (*1*), in the region of maximal $\Delta\lambda$ (*2*) and for a high pump level (*3*).

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application because of inevitable parameter variations during their fabrication. The use of SLDs with a redundant output power and introduction of a controlled input optical attenuator into the interference schemes may be a simple solution; however, it is hardly applicable to serial OCT systems because it would call for a reconstruction of optical and mechanical components and also electronic control systems.

For this reason, the development of QW-based SLDs allowing the output power to be varied smoothly over a wide range and the bandwidth to keep as large as possible looks very promising. The obvious solution is a SLD design with inhomogeneous injection. It is this kind of SLDs that is investigated experimentally in this paper.

2. Experimental samples

A semiconductor single quantum-well (SQW) GaAlAs/GaAs heterostructure was used for the fabrication of SLD samples. Grown by metalloorganic vapor-phase epitaxy, it has a thinner active layer than the structures which are usually used in devices of the SLD-37 series [8]. To perform the rapid analysis of newly grown epiwafers, small-size light-emitting diode (LED) samples are usually made from these wafers. The emission spectrum of such LEDs does not suffer from absorption in non-injected areas of the crystal and superluminescence, and corresponds to almost 'pure' spontaneous emission. These spectra help to predict spectral parameters of particular SLDs based on this heterostructure and, after fabrication of devices and measurements of their parameters, to calculate the optical-gain spectra for different pump levels. The spontaneous-emission spectra of the test LEDs made from the SQW wafer under consideration are shown in Fig. 2. At 'equalised' spectral maxima, the half bandwidth is greater than 100 nm, and the inter-maximum spacing is about 40 nm. This indicates that a SLD with a record bandwidth (over 70 nm) for this particular near-IR spectral range is quite feasible. Further experiments have confirmed the prediction.

Two types of SLDs were made to carry out comparative investigations. Type I samples had a conventional design. Their straight active channel represented a 4.0-μm-wide ridge waveguide. The axis of the active channel made the angle 7° with respect to the normal to the AR-coated facets of the crystal. The length of the active channel L_a could be varied from 100 to 1600 μm with the step of 100 μm. Two-section type II SLDs (Fig. 3) had $L_a = 1200$ μm and only one design distinction from type I samples: in the middle of their active channel they had a 40-μm-wide ion-etched groove where a contact p^+-GaAs layer was completely removed. Electrically separating two SLD sections, the groove had an electrical resistance of about 2.5 kΩ. The measurements of output parameters of the samples of both types involved a continuous injection regime and temperature stabilisation at 25 °C by means of the PILOT-4 electronic drivers.

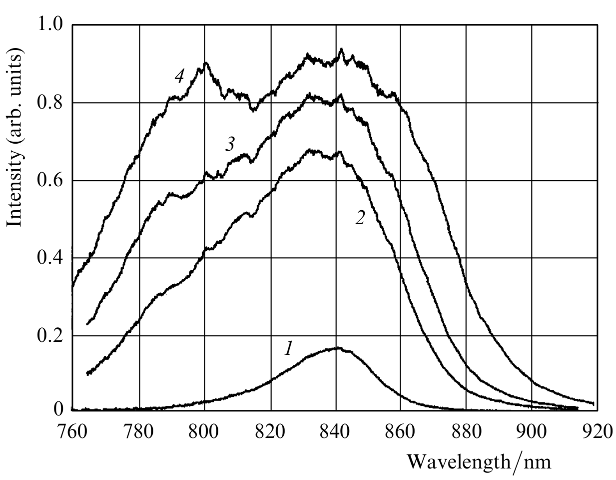

Figure 2. Emission spectra of sample LEDs based on experimental SQW heterostrustures for injection current densities 0.2 (*1*), 1.1 (*2*), 1.8 (*3*) and 3.5 kA cm^{-2} (*4*).

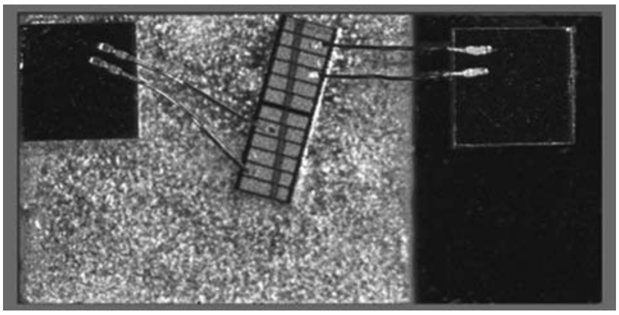

Figure 3. Photograph of a two-section SLD.

3. Experimental results

The main output parameters of the type-I SLDs with different active channel lengths operating in the regimes corresponding to the largest bandwidth $\Delta\lambda$ (equalised spectral maxima) are given in Table 1. For samples with $L_a > 1200$ μm, the overheating of the diode and saturation of its output power or its catastrophic degradation did not allow us to equalise spectral maxima in the cw operation regime. The data show that the output power in this particular operation regime is strongly dependent on L_a. With a threefold change in L_a (from 400 to 1200 μm), the power of emission into the free space (P_{FS}) grows by almost two orders of magnitude. The bandwidth $\Delta\lambda$ decreases only slightly, remaining within the range of 70 – 80 nm. The spectral drop ΔS also grows threefold, but does not exceed 50 %. These data indicate clearly that keeping a particular level of the output power is a difficult problem.

Table 2 gives the same output parameters for the two-section type II SLD. In this experiment, we varied operation currents I_1 and I_2 (and, therefore, the spectra of spontaneous emission and optical gain of the first and second sections) to get different output powers with equalised spectral maxima. As was mentioned above, we used the same single-layer SQW wafer and the same photolithographic masks to make type I and II SLD samples. Extra photolithographic and etching processes enabling electrical isolation of the sections of type II samples makes the only difference in fabrication.

Unfortunately, in fabrication of type II SLDs (in ion-etching formation of the ridge waveguide, to be exact) excessive etching occurred. As a result, the lateral electrical and optical confinement was more rigid for these samples

Table 1. Main output parameters of type I SLD samples with different lengths of the active channel.

$L_a/\mu m$	I_{SLD}/mA	$J/kA\ cm^{-2}$	P_{FS}/mW	P_{SM}/mW	λ_m/nm	$\Delta\lambda/nm$	ΔS (%)	R (%)
400	65	4.1	0.8	0.2	819	80	15	0.3
600	100	4.2	2.0	0.8	820	77	22	0.3
800	140	4.4	6.4	2.8	821	74	31	0.4
1000	200	5.0	21.5	10.0	822	71	39	0.5
1100	270	6.1	40.0	19.0	822	70.5	41	0.6
1200	350	7.3	72.5	34.3	823	70	44	0.7

Note: J is the injection current density; P_{FS} is the free-space output power; P_{SM} is the power at the single-mode fibre output; λ_m is the central wavelength; ΔS is the depth of the spectral drop; R is the depth of residual spectral modulation by Fabry–Perot modes (Ripple).

Table 2. Main output parameters of type II SLD samples for different combinations of injection currents I_1 and I_2.

I_1/mA	I_2/mA	P_{FS}/mW	P_{SM}/mW	λ_m/nm	$\Delta\lambda/nm$	ΔS (%)	R(%)
105	0	2.77	0.805	820.6	76.6	35	0.2
128	10	5	1.6	820.2	76.5	58	0.2
170	15	10.84	4.01	818.9	75.3	70	0.2
192	20	16.1	6.04	818.7	74.4	73	0.3
251	30	30.93	12.11	818.9	72.5	66	0.7
289	45	46.15	17.96	820	69.9	54	1
281	75	62.98	25.54	821.4	67.8	44	1
266	95	71.8	29.54	822.1	67.7	43	1.2
239	125	79.88	32.6	822.8	68.6	46	1.2
196	196	90.22	37.12	824.4	69.3	53	1.5

than for type I samples. For this reason, the radiation divergence in the p–n junction plane became wider, and the coupling efficiency into a single-mode fibre had a lower value (compare P_{FS} and P_{SM} of type I and II samples). Besides, the external efficiency of two-section SLDs increased (compare P_{FS} of homogeneously pumped type I samples with $L_a = 600$ and 1200 μm and type II samples at $I_2 = 0$ and $I_1 = I_2 = 196$ mA). For the same reason, the spectral maxima of type II samples were sharper (Fig. 4) and the inter-maxima drops and residual modulation – deeper. These differences can be eliminated by improving the technological processes of SLD fabrication.

The experimental demonstration of the possibility to set any output power from a wide range of allowable values by varying injection currents of a two-section SLD and keeping the emission bandwidth at a maximum level can be regarded as the main result of the research. The use of a two-channel driver for controlling regime-setting currents I_1 and I_2 is not always convenient and sometimes is unacceptable at all. However, when a SLD is required to ensure a fixed level of the output power with a wide enough bandwidth (it is just what is needed in almost all OCT systems), this problem can be solved easily. When a module is assembled, it is possible to put an adjustable resistor between the contacts of the first and second sections to provide a necessary proportion of injection currents fed through a corresponding pin-contact of the module. For users, this module does not differ from conventional modules containing homogeneously injected SLDs. Moreover, this design allows application of conventional automatic power control (APC) systems by using a signal from a built-in monitoring photodiode receiving the emission coming from the rear facet of the SLD. In the case of inhomogeneous injection, the spectrum of this light can differ greatly from the spectrum of the output light from the front facet, its power being smoothly dependent on the total current.

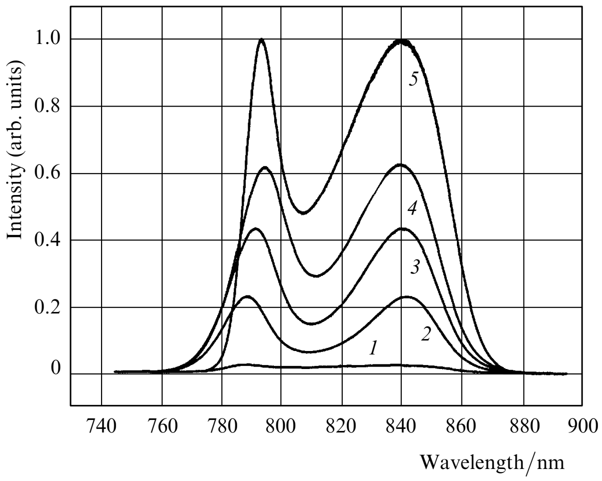

Figure 4. Spectra of the output emission of a two-section SLD for different combinations of injection currents: $I_1 = 105$ mA, $I_2 = 0$ mA (*1*), $I_1 = 192$ mA, $I_2 = 20$ mA (*2*), $I_1 = 251$ mA, $I_2 = 30$ mA (*3*), $I_1 = 289$ mA, $I_2 = 45$ mA (*4*), $I_1 = I_2 = 196$ mA (*5*).

4. Conclusions

Our experiments showed that the use of a two-section QW SLD design gives an additional degree of freedom to manufacturers of broadband light-emitting modules. It allows them to vary smoothly the output power of each particular module within a wide range and at the same time to keep the spectral width as large as possible for a particular heterostructure. For a two-section SLD based on the experimental SQW GaAlAs/GaAs heterostructure, the output power varied from 2.8 to 90.2 mW with half bandwidth $\Delta\lambda$ keeping at about 70 nm.

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