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# High-power broadband superluminescent diodes emitting in the 1000 – 1100-nm spectral range

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***Abstract*. The physical parameters of superluminescent diodes (SLDs) based on a quantum-well heterostructure with two active (InGa)As layers are studied. The optical power coupled into a single-mode fibre was 0.5 – 30 mW and the width of the emission spectrum was 30 – 120 nm depending on the SLD active-channel length. The use of such SLDs in BroadLighter combined broadband radiation sources will provide emission covering the near-IR region between 800 and 1100 nm.**

***Keywords***: *superluminescent diode, quantum-well heterostructure, optical coherence tomography.*

## 1. Introduction

During the past decade, a new method for medical diagnostics – optical coherence tomography (OCT) has been successfully developed [1]. The basic requirements imposed upon optical radiation sources for OCT are their high brightness, which provides a sufficiently deep penetration of radiation in tissues and allows the use of single-mode fibreoptic interferometric schemes, and a low degree of coherence determining the spatial resolution of the method. The OCT systems are most commonly used at present in ophthalmology. Until recently, broadband radiation sources in the near-IR range from 800 to 950 nm were most often used in these systems. This spectral range corresponds to the transparency window of the eye liquid [2]. However, at present the spectral range between 1000 and 1100 nm also attracts great attention [3]. It was shown in [4] that due to attenuation of optical scattering in the retina and a considerable increase in the eye-safe exposure, this spectral range is preferable for some types of ophthalmic OCT systems.

In ophthalmic studies, radiation sources based on ytterbium-doped fibre amplifiers – tunable lasers or sources of amplified spontaneous radiation, as well as superluminescent diodes (SLDs) are used. The advantages of the latter are well known, but unfortunately commercial SLDs of this spectral range considerably rank below ytterbium-doped fibre sources in their output power. For example, the output power ex a single-mode fibre in an SLD-481-MP module (emitting at 1045 nm with the half-width of the emission spectrum equal to 40 – 45 nm) does not exceed 2.0 mW. In this paper, we studied SLDs based on a double (InGa)As/(AlGa)As quantum-well heterostructure (DQW) optimised for increasing the output power and broadening the emission spectrum.

## 2. Experimental samples

A semiconductor (InGa)As/(AlGa)As heterostructure was grown by the method of MOS hydride epitaxy in a Sigmos-130 horizontal quartz reactor with a rotating graphite substrate support. The growth temperature was 720 °C at a pressure of 60 Torr in the reactor. The group III and V elements were obtained from $Al(CH_3)_3$, $Ga(C_2H_5)_3$, $In(CH_3)_3$, and $AsH_3$. Compounds $Zn(C_2H_5)_2$ and $SiH_4$ were used as ligatures of the n- and p-conduction, respectively, and hydrogen was used as a carrier gas. The epitaxial growth was performed on n-GaAs (100) substrates.

Figure 1 shows schematically the band diagram of the grown heterostructure. The active region of the heterostructure consisted of two InGaAs quantum wells separated by the GaAs barrier. The geometry of the quantum wells

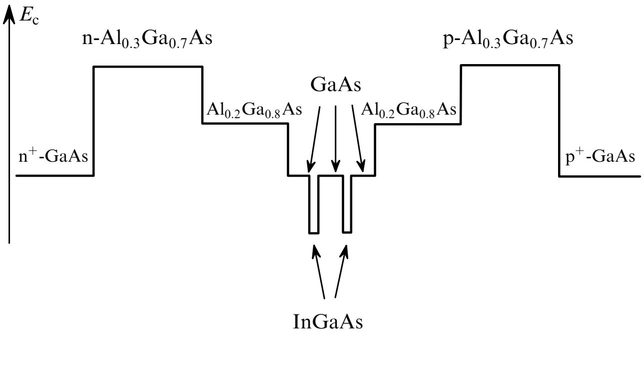


**Figure 1.** Schematic view of the layer structure and the band diagram of a double quantum-well structure.

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was selected to provide a broad emission spectrum. The active region was placed between the 0.15-μm thick $Al_{0.2}Ga_{0.8}As$ waveguide layers and 1.5-μm thick $Al_{0.3}Ga_{0.7}As$ emitter layers. The heterostructure ended with the 0.5-μm thick $p^+$-GaAs contact layer.

We fabricated SLDs with the tilted active channel, which were similar to those described in [5]. The lateral optical confinement was provided by a ridge of width $w = 4$ μm. The active channel length $L_a$ could be varied from 200 to 1600 μm depending on the position of cleaves forming the facets of the crystal. The positive optical feedback was suppressed by orienting the active channel length at an angle of 7° with respect to the normal to the crystal facets. In addition, multilayer reflection coatings of alternating $Al_2O_3$ and $ZrO_2$ layers were deposited on the facets. Crystals were soldered the p-side up on a copper heat sink. All the measurements were performed with thermally stabilised SLDs in the regime of spatially homogeneous injection.

## 3. Spectral and power characteristics of SLDs

It is known that the spectral characteristics of QW SLDs are much more complicated than those of SLDs based on 'volume' double heterostructure (DH) or separate-confinement DH lasers [5, 6]. They are determined by the overlap of the spontaneous emission and optical gain spectra and depend on many factors such as the injection current density, its spatial inhomogeneity (if any), the active channel length and temperature.

The maxima of the emission spectra of SLDs studied in the paper are located at 970–980 nm and 1020–1030 nm. The typical evolution of the superluminescence spectrum with increasing the injection current is shown in Fig. 2a. The maximum width $\Delta\lambda$ of the spectrum, corresponding to the minimum coherence length $L_{coh}$, is achieved when the intensities of the emission maxima become equal [curve (*2*)]. For SLDs with different $L_a$, this is achieved for different injection currents $I$ and different output powers $P_{out}$. This is illustrated by a family of light–current characteristics (Fig. 2b), where the operating points corresponding to the maxima of $\Delta\lambda$ are indicated. For $L_a \geqslant 1200$ μm, we have failed to equalise the spectral maxima.

Table 1 summarises the power, spectral, and polarisation characteristics of the SLDs in the regime of the maximum spectral width at the operating temperatures 25 and 15 °C.

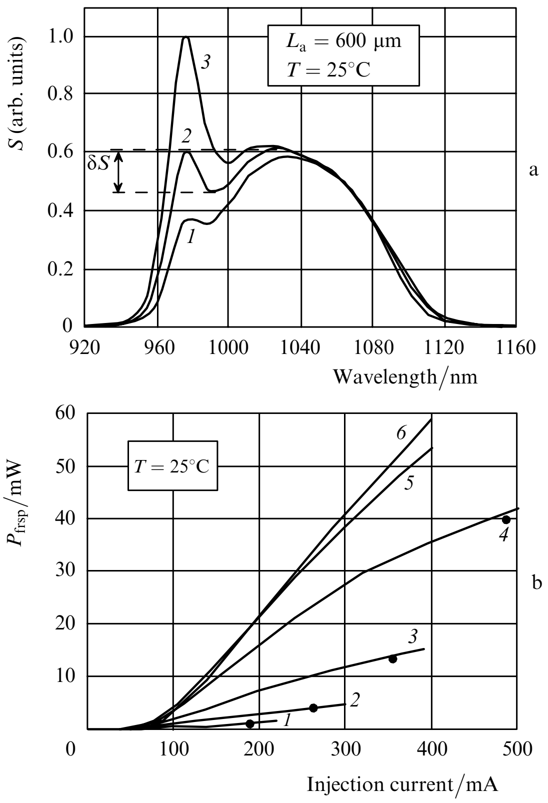


**Figure 2.** Emission spectra of the SLD with $L_a = 600$ μm for injection currents $I = 170$ (*1*), 192 (*2*) and 220 mA (*3*) and the light–current characteristics of SLDs with the active-channel length $L_a = 600$ (*1*), 800 (*2*), 1000 (*3*), 1200 (*4*), 1400 (*5*), and 1600 μm (*6*) (b).

Our measurements lead to the following conclusions:

(i) By increasing $L_a$, we can obtain a considerable advantage in the output radiation power upon a weak decrease in $\Delta\lambda$ and a slight increase in $\delta S$; however, the operating current increases considerably;

(ii) the output radiation power noticeably increases with lowering the operating temperature;

(iii) the coefficient $K_{in}$ of radiation coupling increases with increasing the output power, which is related to a decrease in the fraction of spontaneous radiation;

(iv) radiation is strongly polarised, the polarisation degree noticeably increasing with the output power, which

**Table 1.** Physical parameters of SLDs with different active-layer lengths $L_a$ for the maximum width of the emission spectrum.

| $L_a$/μm | $T$/°C | $I$/mA | $J$/kA cm$^{-2}$ | $P_{frsp}$/mW | $P_{sm}$/mW | $K_{in}$ (%) | $\lambda_m$/nm | $\Delta\lambda$/nm | $\delta S$ (%) | TE/TM | $L_{coh}$/μm |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 600 | 25 | 192.0 | 8.0 | 1.20 | 0.36 | 30 | 1027.6 | 120.5 | 24 | 48 | 8.76 |
| | 15 | 188 | 7.83 | 1.45 | 0.44 | 30.3 | 1023.3 | 118.5 | 26 | 53 | 8.84 |
| 800 | 25 | 264 | 8.25 | 4.4 | 1.55 | 35.2 | 1027.3 | 114.5 | 30 | 96 | 9.22 |
| | 15 | 256 | 8.0 | 5.8 | 2.05 | 35.3 | 1022.8 | 112.5 | 33 | 97 | 9.30 |
| 1000 | 25 | 355 | 8.88 | 13.8 | 5.55 | 40.2 | 1029.5 | 111.5 | 36 | 140 | 9.51 |
| | 15 | 357 | 8.93 | 19.4 | 8.0 | 41.2 | 1025.1 | 109.5 | 39 | 155 | 9.60 |
| 1200 | 25 | 490 | 10.21 | 42.1 | 18.3 | 43.5 | 1029.6 | 108.5 | 37 | 200 | 9.77 |
| | 15 | 529 | 11.02 | 57.4 | 25.3 | 44.1 | 1022.5 | 107.5 | 40 | 215 | 9.73 |

Note: $J$ is the injection current density; $P_{frsp}$ is the output radiation power in a free space; $P_{sm}$ is the radiation power at the end of a single-mode fibre (we used a single-mode Corning Pure Mode 720 fibre with a wide-aperture spherical microlens at the input end, which was optimal for the given spectral range); $K_{in}$ is the coefficient of radiation coupling into the fibre; $\delta S$ is the spectral dip depth (Fig. 2a); TE/TM is the polarisation ratio.

is also caused by a decrease in the fraction of spontaneous radiation.

Figure 3 shows the typical coherence function (CF) of these SLDs recorded with an Advantest Q8347 optical analyser based on a Michelson interferometer. The CF has a complex-shaped central pedestal, which is typical for spectral lines of shape strongly different from a Gaussian. However, the presence of a narrow spectral peak suggests that these SLDs can be efficiently used in high-resolution OCT systems.

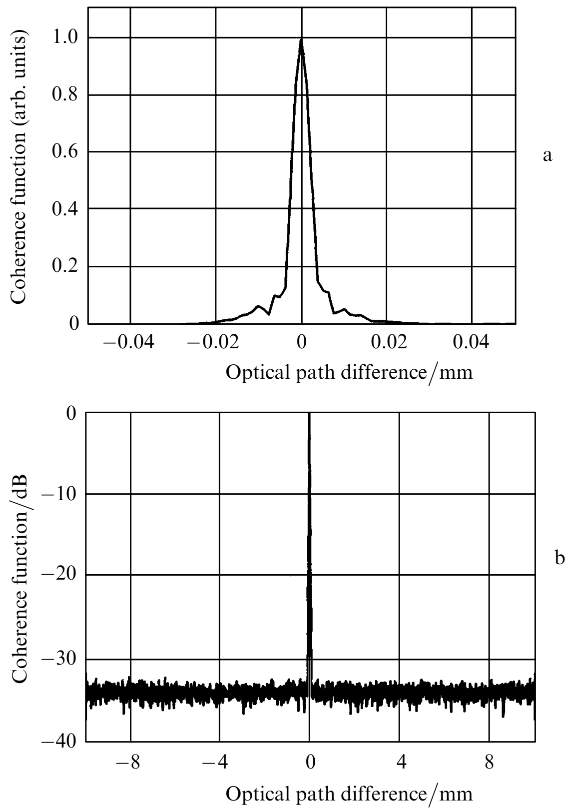


**Figure 3.** Coherence function of the SLD ($L_a = 600$ μm, $I = 190$ mA): the central peak (a) and the general view of the CF (b) ($T = 25$ °C).

We have not found any noticeable degradation of the output characteristics of SLDs during our studies. It can be expected that higher-power SLDs with a higher operating current will have a shorter operating life, which will require the search for a compromise between the output characteristics and the assumed service life. We began to study the aging process in SLDs of this type, which requires a long time.

## 4. Conclusions

Note that the width of the emission spectrum and the output power of SLDs studied in this paper considerably exceed those of commercial SLDs for this spectral range and of laboratory samples with record values of these parameters. In addition, the design of our SLDs (without an optical absorber) allows their use as broadband travelling-wave laser amplifiers.

The SLDs developed in the paper are promising for applications in broadband BroadLighter radiation sources. These sources are based on the superposition of radiation from several SLDs with partially overlapped spectra by using special broadband fibreoptic couplers [2]. Figure 4 presents the emission spectra of such combined sources, where the SLDs described in this paper are used as the longer-wavelength radiation source. The spectrum of the two-channel combined radiation source (Fig. 4a) is obtained by using quantum-well SLDs emitting in the 920-nm region [5]. The median wavelength of such a two-channel source is 970 nm and the spectral width is ~ 210 nm (the coherence length is 4.6 μm). In addition, a four-channel combined radiation source with the record spectral width exceeding 300 nm and the median wavelength at ~ 930 nm (the coherence length is 2.9 μm) can be developed based on a commercial BroadLighter T-870 radiation source. The emission spectrum of this source is shown in Fig. 4b. Note that these devices have no analogues among semiconductor radiation sources with respect to a combination of the output power and spectral characteristics.

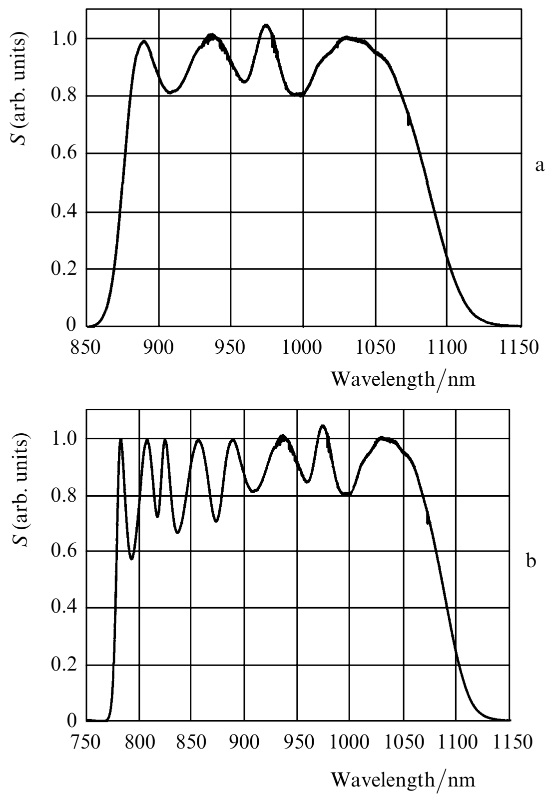


**Figure 4.** Emission spectra of multichannel combined radiation sources based on SLDs studied in the paper: two-channel (a) and four-channel (b) combined radiation sources.

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## References

1. Fercher A.F., Drexler W., Hitzenberger C.K., Lasser T. *Rep. Prog. Phys.*, **66**, 239 (2003).
2. Adler D.S., Ko T.H., Konorev A.K., Mamedov D.S., Prokhorov V.V., Fujimoto J.J., Yakubovich S.D. *Kvantovaya*

*Elektron.*, **34** (10) 915 (2004) [*Quantum Electron.*, **34** (10) 915 (2004)].

3. Povazay B., Bizheva K., Herman B., Unterhuber A., Sattmann H., Fercher A.F., Shubert C., Ahnelt P.K., Mei M., Holzwarth R., Wardworth W.J., Knight J.C., Russel P.St.J. *Opt. Express*, **11**, 1980 (2003).
4. Unterhuber A., Povazay B., Herman B., Sattmann H., Shavez-Pirson A., Drexler W. *Opt. Express*, **13**, 3252 (2005).
5. Mamedov D.S., Prokhorov V.V., Yakubovich S.D. *Kvantovaya Elektron.*, **33** (6), 471 (2003) [*Quantum Electron.*, **33** (6), 471 (2003)].
6. Batovrin V.K., Garmash I.A., Gelikonov V.M., Gelikonov G.V., Lyubarskii A.V., Plyavenek A.G., Safin S.A., Semenov A.T., Shidlovskii V.R., Shramenko M.V., Yakubovich S.D. *Kvantovaya Elektron.*, **23** (2) 113 (1996) [*Quantum Electron.*, **26** (2) 109 (1996)].