Quantum Electronics **42** (11) 961–963 (2012)

PACS numbers: 42.55.Px; 78.66.–w; 42.60.Lh
DOI: 10.1070/QE2012v042n11ABEH014981

Nearest-IR superluminescent diodes with a 100-nm spectral width

S.N. Il'chenko, M.A. Ladugin, A.A. Marmalyuk, S.D. Yakubovich

Abstract. **This paper presents an experimental study of quantum well superluminescent diodes with an extremely thin (InGa)As active layer. Under cw injection, the output power of such diodes is several milliwatts, with a centre wavelength of 830 nm and emission bandwidth of about 100 nm.**

Keywords: *superluminescent diode, optical coherence tomography.*

1. Introduction

Shortly after the advent of quantum well semiconductor laser heterostructures (nanoheterostructures), their gain bandwidth was shown to reach ~100 nm [1]. In 1996, Batovrin et al. [2] experimentally demonstrated superluminescent diodes (SLDs) with a centre wavelength of 820 nm and a three-band spectrum 98 nm in width. This width was however obtained using pulsed–cw combined injection and related to an average spectrum. The instantaneous spectral width, which determines the coherence length of the laser output, was approximately one-third smaller. Later, cw SLDs with an emission bandwidth of up to 91.5 nm were demonstrated in the same spectral range [3]. Those results were not put to practical use, presumably because the asymmetric four-layer nanoheterostructure used in the active region is difficult to obtain with reproducible parameters.

At present, there are commercial broadband quantum well SLDs operating in various spectral ranges. They are used in a variety of applications, with optical coherence tomography (OCT) holding the lead [4]. In this application area, the spectral width is a key parameter which determines the spatial resolution of a particular interference technique. For SLDs with centre wavelengths above 900 nm, the 100-nm bandwidth level has long been surpassed [5, 6]. The bandwidth of SLDs operating at the shortest IR wavelengths, near the upper end of the visible spectrum, currently does not exceed 70 nm. Recall that, at the 'popular wavelengths' of 1060, 980 and 830 nm, a 100-nm bandwidth corresponds to energy intervals of 0.11, 0.13 and 0.18 eV, respectively.

Note that it is nearest-IR broadband SLDs that are typically used as light sources in the most widespread OCT systems for ophthalmology, because this spectral region corresponds to the main transmission window of vitreous humour. To date, more than ten thousand SLD-37 Russian-made SLD modules, with a typical spectral width of 50 nm, have been manufactured. These are successfully employed in OCT systems all over the world. The SLD-35 modules, with a spectral width of up to 70 nm, have not reached such a level of production, but about a hundred science centres, universities and companies involved in OCT research and development have bought these modules – either as a separate source or incorporated into BroadLighter combination light sources. Similar SLD modules have been successfully commercialised by EXALOS AG (EXS21 Series) and DenseLight Semiconductors Pte Ltd (DL-CR8 Series). There is, no doubt, a strong need for enhanced bandwidth SLDs operating in the spectral region in question.

2. Experimental results

Prototype SLDs were fabricated using a separate confinement heterostructure. The geometry of its layers and the contact, emitter and waveguide layer compositions were typical of the (AlGa)As system. One distinctive feature of the heterostructure was the quantum well active region design, which ensured the possibility to obtain a centre wavelength of its gain band near 840 nm and drive apart the spectral peaks corresponding to the quantum transitions from the ground and excited states. This cannot be achieved with GaAs quantum wells, commonly used in heterostructures for the spectral region in question. Our calculations suggest that the above parameters can be obtained using strained ultrathin (InGa)As quantum wells with low indium content. This approach enables an increase in the potential barrier height of quantum wells, which, together with their small width, offers the possibility of increasing the separation between size quantisation levels to a necessary value, without changing the centre wavelength. The calculations were made for a rectangular quantum well.

An epitaxial (InGa)As/(AlGa)As single quantum well structure was grown by low-pressure metal-organic vapour phase epitaxy on (100) GaAs substrates in a horizontal flow reactor. The precursors of the Group III metals were trimethylaluminium, triethylgallium and trimethylindium; the arsenic precursor was 100% arsine; and hydrogen was used as a carrier gas. For n- and p-doping, we used a silane–hydrogen

S.N. Il'chenko Superlum Diodes Ltd., P.O. Box 70, 119330 Moscow, Russia;
M.A. Ladugin 'Sigm Plyus' Ltd., ul. Vvedenskogo 3, 117342 Moscow, Russia; e-mail: M.Ladugin@siplus.ru;
A.A. Marmalyuk Open Joint-Stock Company 'M.F. Stel'makh Polyus Research and Development Institute', ul. Vvedenskogo 3, 117342 Moscow, Russia; e-mail: marm@siplus.ru;
S.D. Yakubovich Moscow State Institute of Radio Engineering, Electronics and Automation (Technical University), prosp. Vernadskogo 78, 119454 Moscow, Russia; e-mail: tm.mohax@mail.ru, yakubovich@superlumdiodes.com

Received 19 September 2012
Kvantovaya Elektronika **42** (11) 961–963 (2012)
Translated by O.M. Tsarev

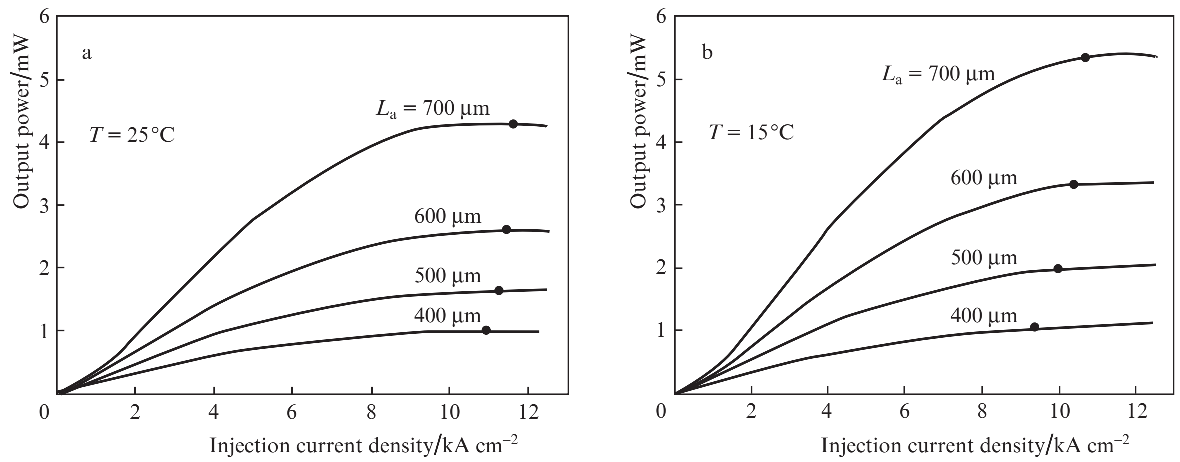

Figure 1. Light–current characteristics of SLDs with different active channel lengths L_a at (a) 25 and (b) 15°C. The dots indicate the conditions corresponding to equal intensities of the spectral peaks.

Table 1. Parameters of SLDs with an $In_{0.04}Ga_{0.96}As$ active layer at different active channel lengths and equal intensities of the spectral peaks.

T/°C	L_a/μm	I/mA	J/kA cm^{-2}	P_{FS}/mW	P_{SM}/mW	λ_m/nm	$\Delta\lambda$/nm	SF (%)	L_{coh}/ μm
25	400	175	10.9	1.0	0.3	830	102	20	6.8
	500	230	11.5	1.4	0.5	832	99	27	7.0
	600	280	11.7	2.5	1.0	834	94	34	7.4
	700	350	12.5	4.0	1.6	836	92	40	7.6
15	400	156	9.4	1.1	0.3	829	101	21	6.8
	500	297	10.0	2.0	0.7	831	98	28	7.0
	600	250	10.4	3.3	1.3	833	94	35	7.4
	700	306	10.7	5.4	2.2	835	92	42	7.6

Note: T, operating temperature; L_a, active channel length; I, injection current; J, injection current density; P_{FS}, free-space output power; P_{SM}, single-mode fibre coupled output power; λ_m, median wavelength; $\Delta\lambda$, emission spectrum FWHM; SF, depth of the spectral minimum; L_{coh}, coherence length.

mixture and diethylzinc, respectively. The growth temperature was varied from 640 to 770°C and the pressure in the reactor was 60–65 Torr. The SLDs had a standard design. The active channel had the form of a 4-μm-wide ridge waveguide inclined at 7° to the end facets of the crystal, which had anti-reflection coatings.

The measurements were made under cw injection at room temperatures. As would be expected, we were able to equalise the intensities of the spectral peaks only at short active channel lengths ($L_a \leqslant 700$ μm). Figure 1 shows the light–current characteristics of the SLDs. Unfortunately, an Ohmic p-contact was made improperly during postgrowth processing of the heteroepitaxial wafer. For this reason, the diodes had an increased differential electrical resistance. Together with their high thermal resistance, characteristic of small devices, this led to thermal saturation of their output power at injection current densities above 5 kA cm^{-2}.

The spectral peaks had equal intensities at a current density of 10–11 kA cm^{-2}. The output power depended significantly on the operating temperature, whereas spectral characteristics changed very little when the temperature was changed by 10°C (Table 1). Figure 2 presents examples of the widest emission spectra and the corresponding coherence functions at active channel lengths of 400 and 700 μm. The full width at half maximum (FWHM) of the spectra is about 100 nm, which is a record level for SLDs in the spectral region in question. CW output powers in the order of several milliwatts are sufficient for a number of metrological applications and some OCT systems. From preliminary life test results, the average lifetime of the SLDs was estimated at 500 h. This lifetime is only acceptable for laboratory instruments.

The operating injection current density of 10^4 A cm^{-2} is not extraordinary for SLDs. We expect that improving the electrical characteristics of SLDs based on the nanoheterostructure studied here will allow us to raise their output power and ensure acceptable reliability. A recent review article by Kostin et al. [7] was titled 'Towards 100nm-wide SLDs at 840 nm band'. The present work is an important step in this direction.

Acknowledgements. We are grateful to A.T. Semenov for initiating this research.

This work was supported in part by the RF Ministry of Education and Science through the federal targeted programme The Scientists and Science Educators of Innovative Russia (Grant No. 14.V37.21.0756).

References

1. Helstein M.M., Melhuys B., Yariv A. *Appl. Phys.*, **54**, 1092 (1989).
2. Batovrin V.K., Garmash N.A., Gelikonov V.M., Gelikonov G.V., Lyubarskii A.V., Plyavenek A.G., Safin S.A., Semenov A.T., Shidlovskii V.R., et al. *Kvantovaya Elektron.*, **23** (2), 113 (1996) [*Quantum Electron.*, **26** (2), 109 (1996)].
3. Ching-Fuh Lin, Bor-Lin Lee. *Appl. Phys. Lett.*, **71**, 1598 (1997).
4. Drexler W., Fujimoto J.G. *Optical Coherence Tomography* (Berlin–Heidelberg: Springer-Verlag, 2008).

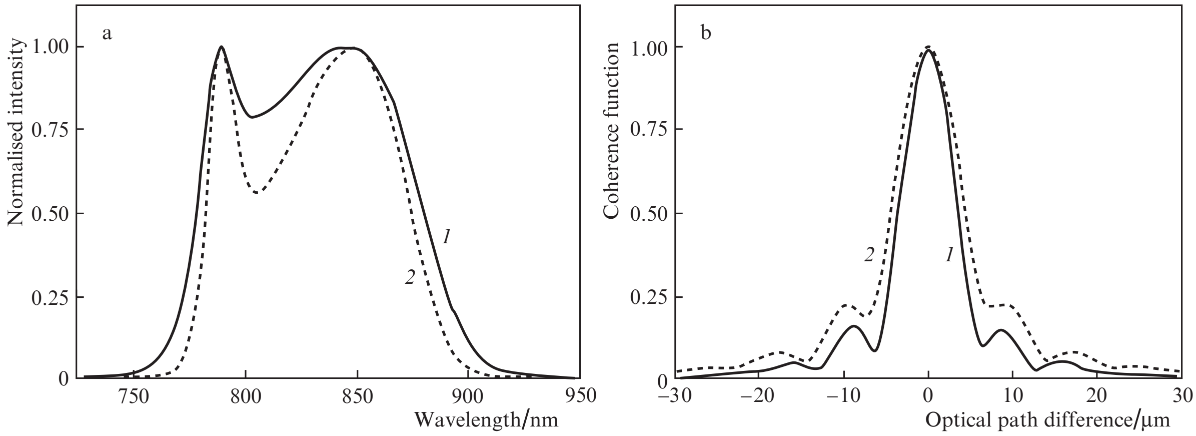

Figure 2. (a) Widest emission spectra and (b) central peaks of the corresponding coherence functions for the SLDs with L_a = (*1*) 400 and (*2*) 700 μm.

5. Mamedov D.S., Prokhorov V.V., Yakubovich S.D. *Kvantovaya Elektron.*, **33** (6), 471 (2003) [*Quantum Electron.*, **33** (6), 471 (2003)].
6. Lapin P.I., Mamedov D.S., Marmalyuk A.A., Padalitsa A.A., Yakubovich S.D. *Kvantovaya Elektron.*, **36** (4), 315 (2006) [*Quantum Electron.*, **36** (4), 315 (2006)].
7. Kostin Yu.O., Lapin P.I., Prokhorov V.V., Shidlovsky V.R., Yakubovich S.D. *Proc. SPIE Int. Soc. Opt.Eng.*, **7139**, 713905-1 (2008).