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Quantum-dot superluminescent diodes with improved performance

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***Abstract*. It is shown that optimisation of the structure of the active channel of quantum-dot InAs/AlGaAs/GaAs superluminescent diodes (SLDs) provides a noticeable increase in their external quantum efficiency. The output cw power coupled out of a single-mode fibre achieves 1.3 and 0.9 W for the emission bandwidth of 27 and 110 nm, respectively. The results of preliminary lifetime tests predict the high enough reliability of these SLDs.**

Keywords: *superluminescent diodes, radiation efficiency, quantum dots.*

1. Introduction

In [1], the experimental samples of superluminescent diodes (SLDs) based on the ten-layer quantum-dot (QD) heterostructure used for manufacturing laser diodes (LDs) [2 – 4] were studied. The results of these studies are of great practical interest because the emission spectrum of SLDs studied in [1] covers the spectral range from 1100 to 1230 nm, which is not mastered so far by commercial SLDs. Unfortunately, the output power of these SLDs is considerably lower than that of traditional SLDs based on separate confinement double heterostructures with 'bulk' and quantum-well active layers. The experimental samples had the ridge active channel of the traditional configuration [5]. The thickness of the incompletely etched p-emitter layer in the latteral regions was about 0.2 μm. It was shown in [6] that the strict lateral confinement (electronic and optical) due to deep etching forming the ridge (up to the complete etching of the waveguide layer) improves the parameters of LDs based on the similar quantum-dot structure by decreasing the threshold current density and increasing the external quantum efficiency. In this paper, we used a similar approach for manufacturing SLD samples, which resulted in the increase in their efficiency. A special attention was paid to the lifetime tests because it is well known that in the case of conventional LDs and SLDs, the approach of the active channel to the semiconductor surface can adversely affect the service life of diodes.

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2. Experimental samples

Figure 1 shows the section of the active channel of SLDs studied in the paper. The active channel represented a single-mode ridge waveguide with ten active InAs QD layers. As mentioned above, the lateral leakage of the injection current and lateral optical confinement determined by the jump in the effective refractive index at the ridge edges strongly depend on the thickness Δh of the incompletely etched layer determining the distance from the semiconductor surface to the upper boundary of the waveguide layer. For samples studied in [1], $\Delta h = 0.2$ μm. We fabricated and studied two batches of samples based on the same heterostructure with $\Delta h = 0$ and 0.1 μm. In the first case, the p-emitter layer was completely removed.

By using the available set of photolithographic templates, we manufactured SLDs with the active channel length L_a up to 1800 μm. SLDs with the maximum length L_a had the maximum external quantum efficiency. Below, we present the results of a comparative analysis of the parameters of the output radiation of SLDs with $\Delta h = 0$, 0.1, and 0.2 mm.

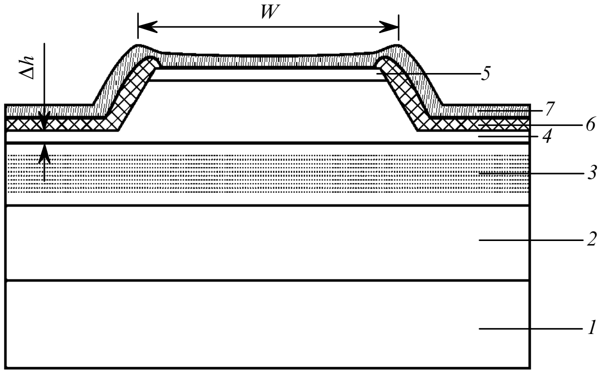

Figure 1. Section of the SLD active channel: (*1*) n$^+$: GaAs substrate; (*2*) GaAlAs n-emitter; (*3*) active waveguide consisting of ten InAs QD layers; (*4*) GaAlAs p-emitter; (*5*) p$^+$: GaAs contact layer; (*6*) isolating cover; (*7*) metal contact; the ridge width is $W = 4.0$ μm.

3. Physical characteristics of SLDs

Figure 2 presents the light – current characteristics of the output radiation of SLDs in the cw injection regime for heatsinks stabilised at the temperature 12 °C. One can see that as Δh was decreased from 0.2 to 0.1, the external quantum efficiency of the SLD considerably increased: the slope of the light – current characteristic in the region of the developed superluminescence before the onset of thermal saturation increased by more than three times. A further decrease of Δh only slightly changed the light – current characteristic of the output radiation (Fig. 2a). The external efficiency weakly increased; however, thermal saturation became noticeable at somewhat lower injection current I. This indicates that the advantage provided by the increase in the lateral confinement is virtually exhausted and the heat removal from the active channel became worse.

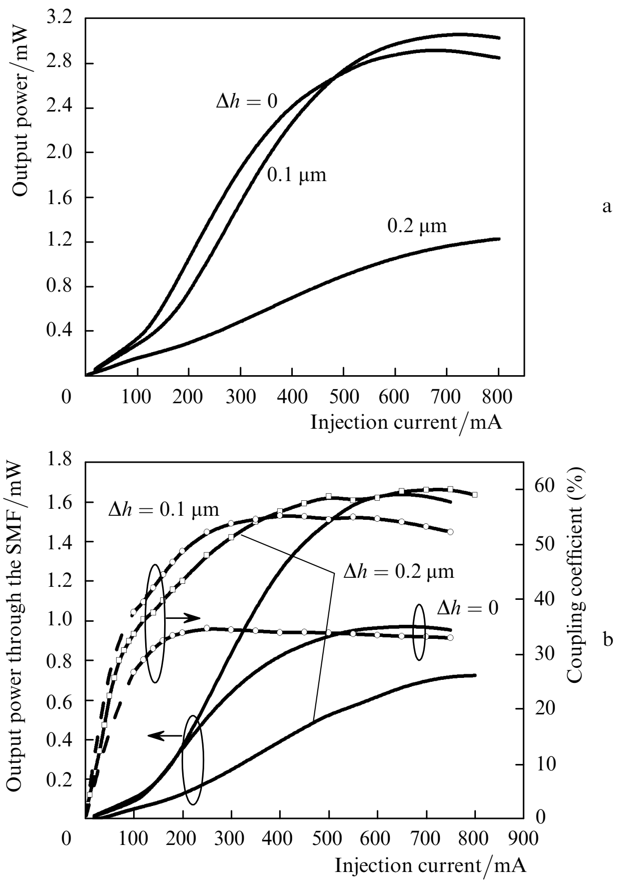

Figure 2. Light – current characteristics of the SLD with $\Delta h = 0$, 0.1, and 0.2 μm for output radiation coupled out directly (a) and through the SMF (b).

As for the light – current characteristic of the output radiation coupled out through a single-mode fibre (SMF) (Fig. 2b), it changes considerably as Δh decreases from 0.1 μm to zero. The coefficient of radiation coupling into the SMF (Corning Pure Mode HI780 fibre with the numerical aperture 0.14) decreases from 53 % – 55 % to 33 % – 34 %. This is explained by the fact that, the guided mode in the p – n junction plane is squeezed with increasing the lateral optical confinement, resulting in the increase in the corresponding diffraction divergence of the diode radiation

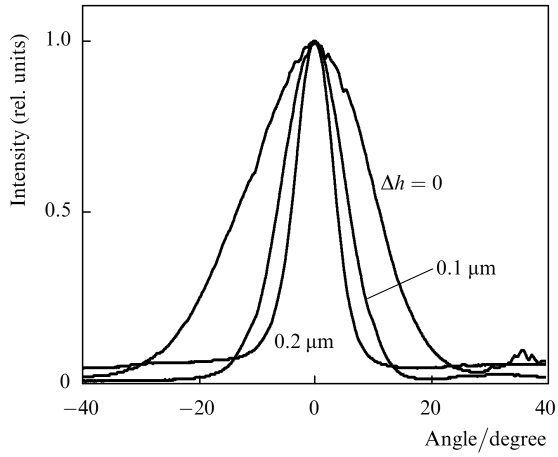

Figure 3. Far-field angular intensity distribution in the p – n junction plane for SLDs with $\Delta h = 0$, 0.1, and 0.2 μm.

(Fig. 3). Measurements were performed by using a cylindrical microlens on the SMF end, which efficiently focuses radiation in the plane perpendicular to the p – n junction, whereas the capture of radiation in the orthogonal plane is restricted by the own numerical aperture of the SMF. In principle, the coupling coefficient can be increased by using a nonstandard SMF with a higher numerical aperture, however, this can strongly restrict the possibilities of practical applications of corresponding SLD modules.

It was shown in [1] that the emission spectra of SLDs based on the heterostructure under study depend in a complicated way on the injected current due to the redistribution of the intensity of quantum transitions from the ground and two excited states. Under certain conditions, which strongly depend on the active-channel length L_a, the emission spectrum can have a bell-shaped ('quasi-Gaussian') profile with the moderate width. Under other conditions, it can be considerably broader and can have two or three maxima.

For practical applications, both variants of the spectrum are of interest. In both cases, as a rule, it is desirable to have the maximum output power. Among the samples studied in this work, SLDs with $L_a = 1800$ μm and $\Delta h = 0.1$ μm had the maximum output power coupled out through the SMF. For the injection current $I \sim 450$ mA, their output power was ~ 1.3 mW and the emission spectrum had the shape shown in Fig. 4a. Unfortunately, up to the total thermal saturation of the power in these samples, we have failed to equalise the spectral maxima in order to obtain the maximum width of the spectrum. This was achieved only for the SLD with $L_a = 1800$ μm and $\Delta h = 0$. For the injection current $I = 780$ mA, we obtained the output power coupled out through the SMF equal to $P_{SM} = 0.9$ mW for the spectrum of width 110 nm (at the −3 dB level). In this case, the output power of these SLDs was 2.5 and 2.9 mW, respectively, which is of practical interest for SLD modules with extraction of radiation through a plane window or a collimating lens. SLDs with $\Delta h = 0$ and $L_a = 1600$ μm had the maximum width of the emission spectrum equal to ~ 115 nm for $I = 680$ mA and $P_{SM} = 0.5$ mW. The two last types of samples (with $\Delta h = 0$), as potentially most prone to degradation, were subjected to lifetime tests in the operating regimes considered above at the temperature stabilised at 25 °C. The results of these tests are presented in Fig. 5. Their analysis according to the standard criterion predicts the

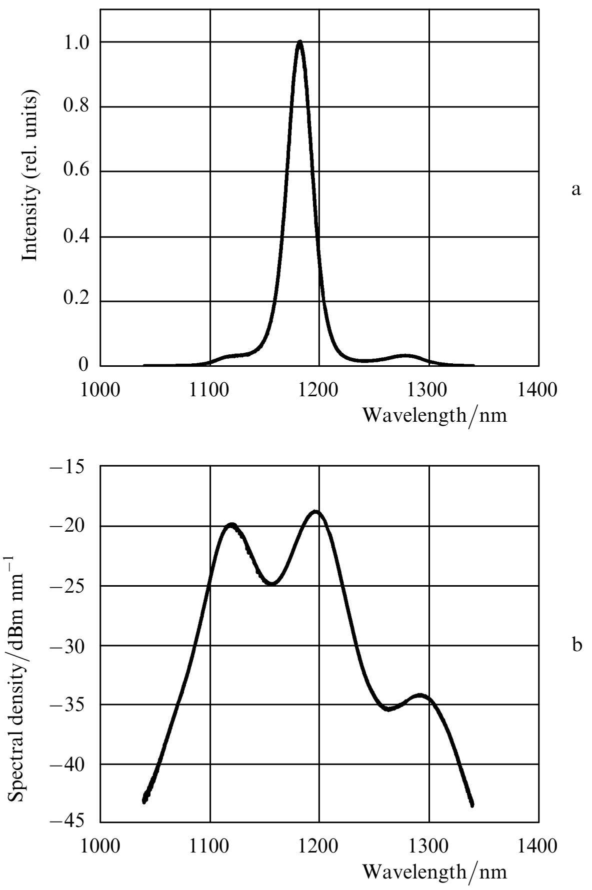

Figure 4. Emission spectra of the SLD with $\Delta h = 0.1$ μm for $I = 450$ mA (a) and $\Delta h = 0$ for $I = 780$ mA (b).

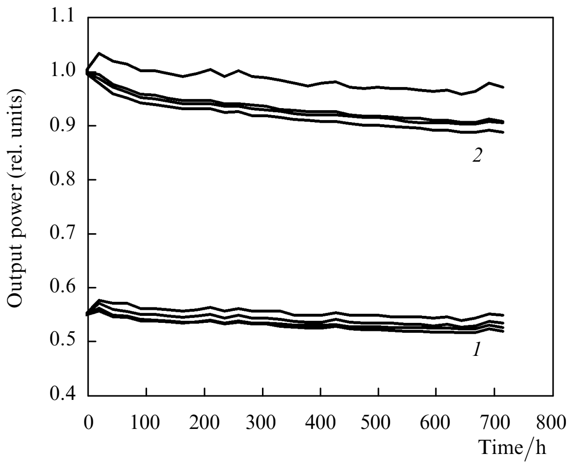

Figure 5. Chronogram of resource tests of the SLD with $L_a = 1600$ μm for $I = 680$ mA (*1*) and $L_a = 1800$ μm for $I = 780$ mA (*2*).

service life of SLDs more than 5000 h for $L_a = 1600$ μm and more than 4000 h for $L_a = 1800$ μm. These values are acceptable in most practical applications.

4. Conclusions

The optimisation of the structure of the active channel of QD heterostructure SLDs resulted in a considerable increase in their external quantum efficiency. The output power was increased by more than three times compared to broadband SLD-541 and narrowband SLD-551 prototypes described in [1].

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