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High-power superluminescent diodes with non-injection output sections

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***Abstract*. Superluminescent diodes based on a separate-confinement (GaAl)As heterostructure are studied in the 850-nm spectral region. A contact p^+-GaAs layer in the output sections of a narrow active channel of width 4 μm was removed and a metal contact was not deposited. These sections played the role of saturable absorbers. This design provided a significant increase in the catastrophic optical damage threshold and ensured 250 mW of output cw power at the diode facet. The power coupled out through a single-mode fibre in the case of a simplest coupling achieved 110 mW.**

Keywords: *superluminescent diode, saturable absorber, catastrophic optical damage.*

1. Introduction

A tapered active channel is often used in the design of high-power superluminescent diodes (SLDs) and travelling-wave semiconductor optical amplifiers (SOAs) [1 – 5]. They produce the diffracted-limited output radiation power of the order of hundreds of milliwatts or even a few watts from an active element. Many technical applications require the extraction of SLD radiation through a single-mode fibre. This is a difficult technical problem for SLDs and SOAs because the output width of the active channel is much greater than the fibre-mode diameter. Multilens microobjectives, which solve this problem [6, 7], are difficult to manufacture and, in addition, they severely complicate the fibre-to-device alignment. It is mainly for this reason that high-power SLDs and SOAs with a single-mode fibre pigtail are quite expensive and their application is limited.

The aim of this paper was to obtain the maximum output cw power for SLDs with a narrow ($w = 3 - 5$ μm) active channel. Efficient coupling (~ 50 % of power) of radiation from such SLDs into a single-mode fibre is simple with a microlens on the fibre facet. The output power of SLDs is mainly limited by the catastrophic optical damage – a drastic decrease in the output power. The degradation threshold power density for SLDs is noticeably lower than that for laser diodes based on the same heterostructure with the same configuration of an active channel. This is explained by the fact that due to suppression of a positive feedback in SLDs, their external quantum efficiency is lower than that of diode lasers, so that the same output power in SLDs is achieved at a higher operating current producing a stronger heating of the active element. In addition, the distribution of the photon and injection current densities along the active channel in SLDs is more inhomogeneous than that in diode lasers. This distribution in a single-pass SLD with a homogeneous active channel has a minimum in the middle of the SLD and a maximum at the output facets. A temperature field in the SLD crystal has a similar distribution.

Considering for definiteness (GaAl)As diodes emitting in the spectral range between 800 and 850 nm, note that the catastrophic optical damage threshold for the best cw diode lasers is observed at radiation power densities exceeding 10^7 W cm^{-2}, whereas this threshold for best conventional SLDs is $(2 - 3) \times 10^6$ W cm^{-2}. The output power of commercially available spatially single-mode 'narrow-channel' diode lasers manufactured by many companies achieves 200 mW. The record laboratory result for SLDs is 105 mW of cw output power [8]. Among commercially available SLDs, the SLD38-HP model probably provides the record output power: 50 mW emitted from the facet and 20 mW coupled out through a single-mode fibre.

Three-section SLDs with non-injection output sections investigated in this paper have the higher catastrophic optical damage threshold, which allowed us to obtain the record output parameters for such SLDs.

2. Experimental samples

We fabricated experimental SLDs (Fig. 1) from a standard bulk (GaAl)As separate-confinement heterostructure, which is used for manufacturing commercially available SLD38-HP devices. The lateral confinement was provided with a ridge structure of width $w = 4$ μm. The axis of the active channel was tilted at an angle of 7° with respect to the normal to the crystal end facets covered by dielectric antireflection coatings (AR). Unlike standard devices with a uniform ohmic contact along the entire active channel, carriers were injected only into the middle part of the active channel of the SLDs of length $L_a = 1000$ μm. A heavily doped contact p^+-GaAs layer in sections of length L_p

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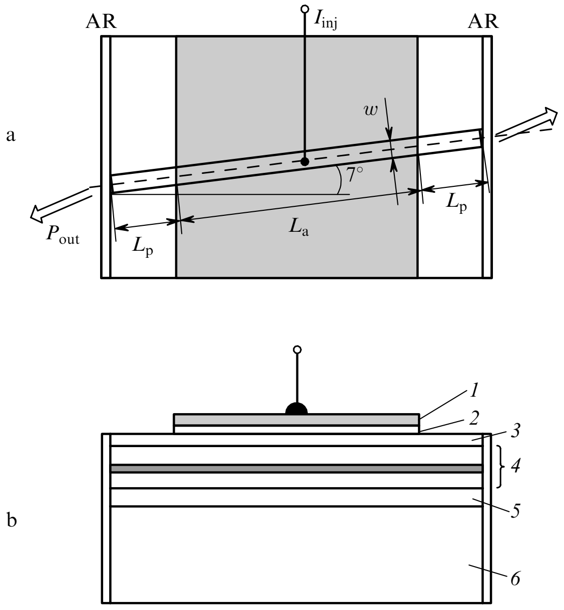


Figure 1. Configuration of a three-section SLD: view from the *p*-side (the [100] plane) (a) and section along the active-channel axis (b): (*1*) metal contact; (*2*) contact p^+ : GaAs layer; (*3*) *p*-emitter; (*4*) three-layer active waveguide (undoped); (*5*) *n*-emitter; (*6*) *n*-substrate.

adjacent to the end facets was removed by the photolithographic method and the surface was not coated with metal.

We studied samples of two types with the lengths of non-injection output sections $L_{\rm p}^{(1)} = 100$ μm and $L_{\rm p}^{(2)} = 200$ μm. These sections were used as saturable absorbers. Similar sections in multisection diode lasers [9] usually have contacts, which have a leakage or are short-circuited to the *N* contact. Their use allows various specific lasing regimes to be obtained increasing considerably, however, the lasing threshold and decreasing the external efficiency compared to a conventional uniform-injection laser. We planned in this study to use readily saturable absorbers described above to reduce the heating of the output sections of SLDs (despite a decrease in the external quantum efficiency) and increase the catastrophic optical damage threshold, thereby increasing the output power.

3. Output characteristics of three-section SLDs

Figure 2 shows the typical light – current characteristics obtained in the continuous injection regime for SLDs of two types thermally stabilised at 25 °C. For comparison also shown is the light – current characteristic [curve (*1*)] for a conventional single-section SLD ($L_{\rm p} = 0$) with the same active-channel length ($L_{\rm a} = 1000$ μm) and fabricated of the same heteroepitaxial wafer as three-section SLDs. The catastrophic optical damage of the single-section SLD was observed at powers 90 – 100 mW, which corresponds to the radiation power density at the active-channel facet equal to $(2.2 - 2.5) \times 10^6$ W cm^{-2}. Three-section SLDs of type I ($L_{\rm p}^{(1)} = 100$ μm) underwent catastrophic optical damage at the approximately doubled output power. Three-section SLDs of type II ($L_{\rm p}^{(2)} = 200$ μm) showed no optical damage for injection currents up to 850 mA (this value was limited by the pump current source) and the output power up to 250 mW (power density up to 6.2×10^6 W cm^{-2}). No slow variation in the output power was observed in experiments at the fixed injection current.

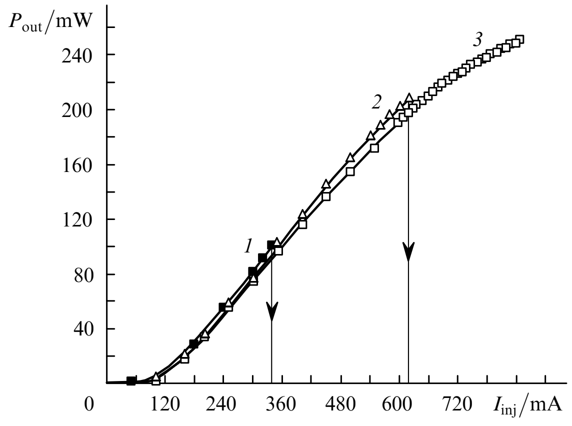


Figure 2. Light – current characteristics of a standard single-section SLD ($L_{\rm a} = 1000$ μm, $L_{\rm p} = 0$) (*1*) and three-section SLDs of types I ($L_{\rm p}^{(1)} =$ 100 μm) (*2*) and II ($L_{\rm p}^{(1)} = 200$ μm) (*3*).

Note that, because the SLDs were completely symmetric, the total output power emitted from both facets achieved 0.5 W, while the averaged slope external efficiency was ~ 0.7 W A^{-1}, which is close to the corresponding value for high-power single-mode diode lasers.

The output radiation of an SLD was coupled into a single-mode Corning Pure Mode HI 780 fibre through a front cylindrical lens. The coupling efficiency was 47 %, which provided above 100 mW emitted from a single-mode fibre. To our knowledge, this is a record value for SLDs of this class. The light – current characteristic of the SLD with a fibre pigtail is shown in Fig. 3. The far-field cross section of the SLD beam was crescent-shaped, the beam half-width divergence being 8.0° in the $p - n$ junction plane and 40.5° in the orthogonal plane (Fig. 4), corresponding to the diffraction limits.

Figure 5 shows the emission spectra of the SLD for the maximum output power. The spectrum recorded at the

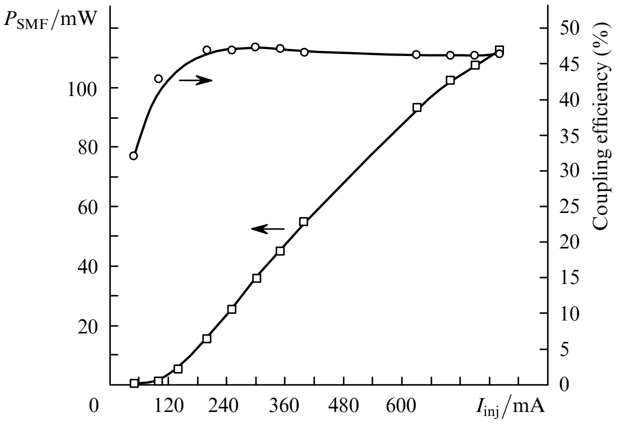
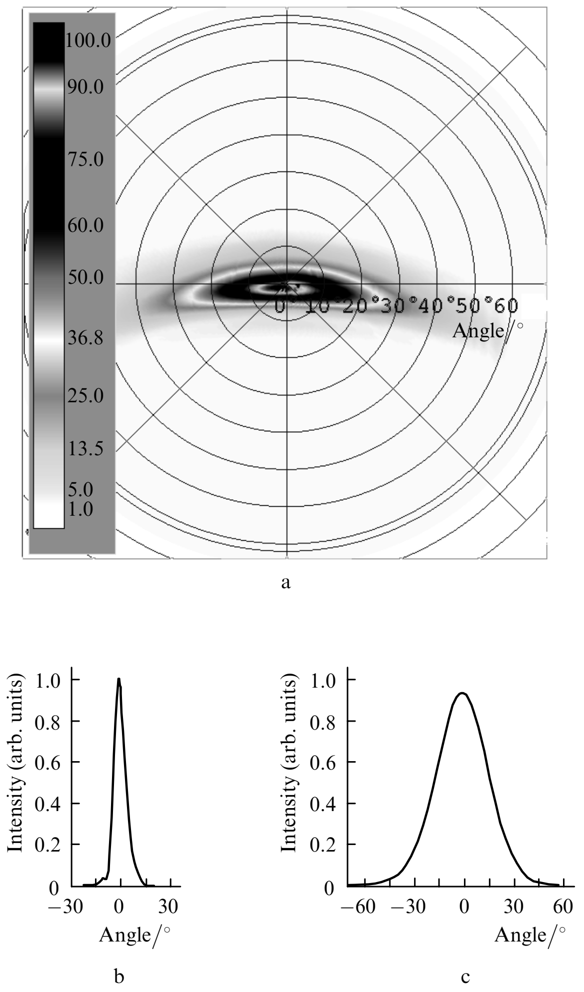


Figure 3. Dependence of the efficiency of radiation coupling into a single-mode fibre on the injection current and the light – current characteristic of the SLD of type II with a single-mode fibre pigtail.



a

b

c

Figure 4. Far-field radiation: the output beam cross section (a) and angular distributions of the radiation intensity in the $p-n$ junction (b) and orthogonal (c) planes.

single-mode fibre output has a smaller width and a deeper periodic modulation by the modes of a Fabry–Perot cavity. This is caused by a parasitic feedback appearing upon reflection of light from a fibre microlens. The modulation depth for radiation emitted directly from the SLD facet [curve (*1*)] did not exceed 3 %, whereas the modulation depth of radiation coupled out through the fibre achieved 10 % – 15 %. This parameter is very important for many practical applications of SLDs. The modulation depth of the spectrum of SLDs with fibre pigtails can be reduced by using microlenses with antireflection coatings.

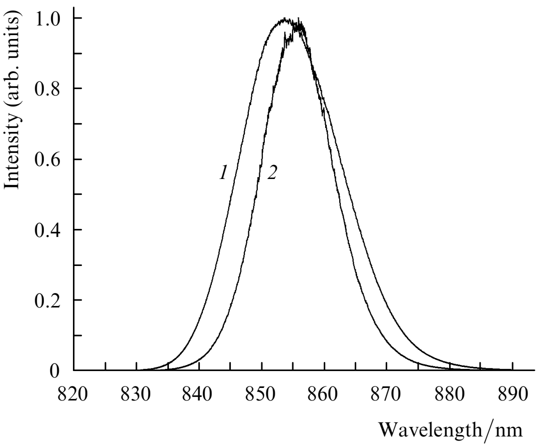


Figure 5. Output emission spectra of the SLD of type II recorded directly (*1*) and through a fibre pigtail (*2*). The injection current is 850 mA.

The problem of reliability of high-power SLDs operating at extremely high current, radiation and thermal loads is quite crucial. A full-scale study of their lifetime requires a long time and a large test statistics. We estimated preliminary the reliability of two batches containing six SLDs of types I and II each, which operated for 288 hours at the temperature 25 °C and a constant injection current 360 mA. The initial output power of SLDs was ~ 100 mW. SLDs of type I did not withstand the test: their output power decreased by more than 50%. As for SLDs of type II, four of the six samples satisfied the test (Fig. 6). We can reliably predict that the service life of these SLDs will exceed 1000 hours, which is admissible for a number of technical applications. They can be used in light-emitting modules with single-mode fibre pigtails emitting 40 – 50 mW. This will require the development of a housing with a better heat removal and a more efficient thermoelectric microcooler compared to those used in standard SLD modules emitting up to 10 mW.

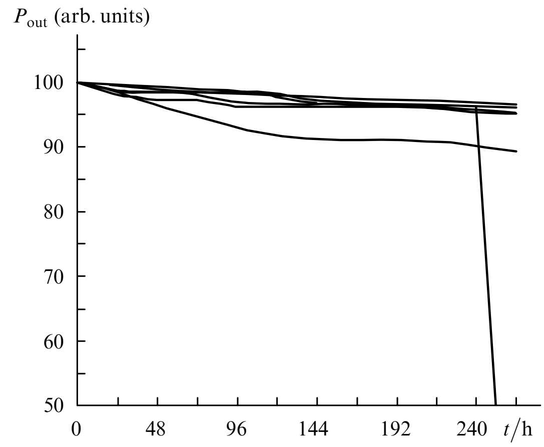


Figure 6. Burn-in test results for a batch of six SLDs of type II for the injection current $I_{\text{inj}} = 360$ mA and temperature $T = 25$ °C.

Note in conclusion that the design of SLDs described above allows one to use them as optical travelling-wave amplifiers. A spectrally matched signal of a sufficient power fed to the input of such a device produces a strong spatial redistribution of photon fields. As a result, the amplifier can produce a higher output power than an SLD at the same injection current. Note that because the frequency of the D2 line of cesium virtually coincides with the maximum of the optical gain of SLDs studied above, they can be used, in particular, in experiments on cooling of atomic ensembles [10].

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