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# Double-pass superluminescent diode with tapered active channel

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*Abstract*. **The optical characteristics of a superluminescent diode (SLD) with a tapered active channel based on a (GaAl)As separate confinement double heterostructure are studied. The one-sided feedback was provided by external reflectors. The cw emission power from the wide-aperture output reached 100 mW, the divergence of the output beam being nearly diffraction-limited. The spectral bandwidth of the emission (the degree of coherence of the SLD) could be varied in a wide range depending on the spectral selectivity of the reflector.**

***Keywords***: *superluminescent diode, semiconductor optical amplifier.*

Semiconductor luminescent diodes (SLDs) are widely used as emission sources for different optical sensors, fibreoptic gyroscopes, optical tomography, and special illuminators. They successfully combine high brightness of laser diodes and low coherence of light emitting diodes. The output power of SLDs is a key parameter in many of these applications.

Structures with a tapered or fan-shaped active channel are successfully used for the fabrication of powerful laser diodes, which ensure the diffraction-limited divergence of output emission [1 – 3]. They usually play a role of a power amplifier of a master oscillator, which is monolithically integrated on a common substrate. To suppress a positive feedback, highly efficient antireflection coatings are applied on the output facets of amplifiers. We used such a tapered structure in this work for the fabrication of a SLD with an enhanced output power.

Experimental samples were fabricated based on a double heterostructure (GaAl)As with a separate confinement emitting at 790 nm. The lateral optical confinement was provided by a ridge waveguide structure. The geometry of the active channel of the SLD is shown in Fig. 1 [the projection on the (100) plane]. Unlike the papers mentioned above, the active channel was inclined with respect to the crystal facets to provide, along with antireflection coatings, a more efficient suppression of the feedback. The multilayer dielectric coatings on the crystal facets ensured the reflectivity $R < 0.1$ % for a chosen angle of the emission incidence (7°). The length $L_1$ of the narrow preamplifier part of the active channel (the width $W_1 = 4$ μm) was varied from 0.4 to 1.0 mm. The length $L_2$ of the tapered part with the output aperture width $W_2 = 40$ μm was 0.4 mm. The crystals were soldered the active channel up on copper heat sinks. The design of the heat sink provided the free output of emission outside from both crystal facets. The temperature was kept constant at 20 °C during the measurements using a temperature control system.

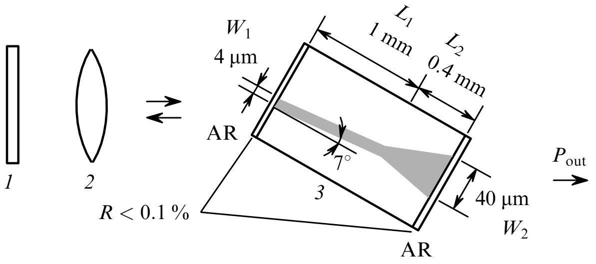

**Figure 1.** The SLD configuration and the experimental scheme: (*1*) external reflector; (*2*) microscopic objective; (*3*) SLD; (AR) antireflection coating; ($P_{out}$) emission power.

Note that commercially available SLDs with a uniform narrow channel ($W = 3 - 5$ μm) based on a similar heterostructure, for instance, SLD-38-MP, have an output power up to 10 mW at an operating current of 140 mA. We failed to achieve a considerable increase in the output power by studying a tapered SLD operating in a traditional single-pass regime of the amplification of its own spontaneous emission. The drastic degradation of the crystal end in the region of the narrow aperture output or an overheating of the diode at large operation currents were limiting factors.

A considerable gain in the output power was obtained using a double-pass amplification regime. To obtain this regime, the narrow aperture output of the SLD was coupled via a collimating AR coated microscopic lens with an external reflector formed by flat nonselective mirrors and diffraction gratings operating in an autocollimating regime. Estimates showed that about 15 % of the output power came back to the active channel and served as an input signal for further amplification when the reflectivity of the mirrors was 90 %. It is known that in contrast to a single-pass SLD, the spatial distributions of local parameters (the optical gain, the spontaneous recombination rate, the photon density) in a double-pass SLD become asymmetric along

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the axis of the active channel. In our case, the use of the double-pass scheme resulted in a considerable increase in the wide-aperture output power, whereas the narrow-aperture output power and the load on the corresponding mirror decreased due to the gain saturation.

The optimum results were obtained for a SLD having the length of the narrow part of the active channel $L_1 = 0.7$ mm. Typical light-current characteristics for the wide-aperture output of such samples are presented in Fig. 2. Note that the area of the section with current injection for the given configuration is approximately 2.5 times larger than for a SLD with a narrow channel of the same length. One can see from curve (*2*) that the continuous output power of over 100 mW is achieved at an injection current of about 350 mA. Curve (*2*) corresponds to the double-pass regime with the use of a plane nonselective mirror with the reflectivity of 90 %. Thus, this SLD allows to obtain a gain in the output power of over an order of magnitude compared to a narrow-channel SLD at the same injection current density ($\sim 3$ kA cm$^{-2}$).

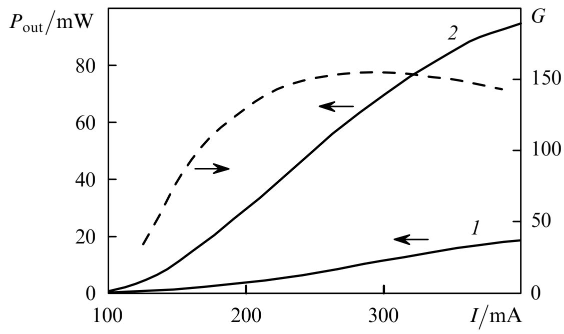

**Figure 2.** Light–current characteristics in a single-pass (*1*) and double-pass (*2*) regimes. The dashed line is a single-pass gain coefficient.

The single-lobe emission pattern in the plane of the active layer first narrows down with increasing injection current and the half-width divergence for the output power of a few mW is around 3.5°, being almost constant with increasing current. This value is three times larger than the diffraction limit, which was formally calculated for a 40-μm-wide aperture and a beam with a uniform intensity distribution, taking into account the inclined beam incidence. The analysis of the near-field pattern showed that the intensity distribution in the plane of the active layer has a bell-like shape with the width at a half-maximum of about 14 μm, i.e., the divergence of emission is close to the diffraction limit.

This fact is quite useful for many practical applications, such as, focusing into a spot of a minimum size, coupling emission into single-mode fibres, the formation of beams of a given configuration, etc. The incomplete filling of the wide output aperture by emission is explained by the mismatch between the opening angle of the tapered section of the active channel (5.7°) and the emission divergence at the output of the narrow preamplifying section. The optimisation of these parameters, for example, a decrease of the opening angle of the taper by increasing its length will result in an increase in the external efficiency of the SLD accompanied by a decrease in the divergence of its emission.

The maxima of supeluminescence spectra at high injection currents ($I > 300$ mA) are located between 792 and 797 nm. The FWHM of the superluminescence bands was 12–14 nm in the single-pass regime. The degree of the residual spectral modulation did not exceed 3 %. The spectral band shape in the double-pass regime was strongly dependent on the spectral selectivity of the external reflector. When a flat nonselective mirror was used, some narrowing of the bands (approximately down to 10 nm) was observed without a noticeable change in the residual modulation degree.

The spectra can be tuned in broad ranges depending on the characteristics of diffraction gratings used and the adjustment of the external reflector. The minimum width of the output emission spectrum (0.12 nm) was achieved with a 1200 lines mm$^{-1}$ reflection grating. The emission spectra obtained in the double-pass regime using the flat mirror mentioned above (curves *1*) and a 600 lines mm$^{-1}$ reflection grating (curves *2*) are presented in Fig. 3. In the latter case, the width of the emission bands, which was determined by the bandwidth of the one-sided feedback, was about 0.25 nm. The spectral density at the maximum of the band tuned from 785 to 803 nm exceeded the background level by more than 25 dB.

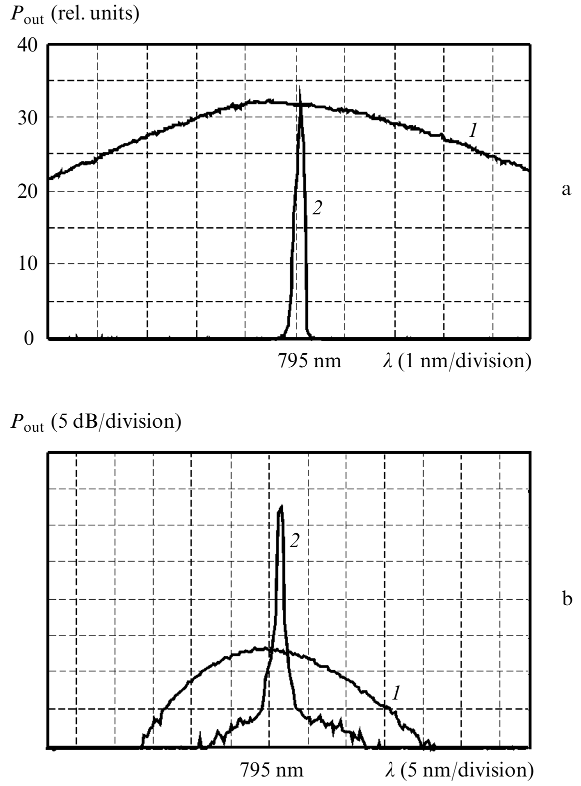

**Figure 3.** Spectra of the output emission in the double-pass regime using a nonselective (*1*) and spectral selective (*2*) reflectors at linear (a) and log (b) scales.

It is obvious that a larger width of the emission spectrum can be obtained by using spectrally selective reflectors with a lower quality. The maximum width can be as large as 10 nm, this value being determined by the optical gain line of the given SLD. In other words, the degree of coherence of such an SLD can be tuned discretely by two orders of magnitude by using an appropriate set of external selective reflectors. Such a light source may be of interest for interferometry and optical tomography. In practice, it is expedient to use a monolithic and miniature fibreoptic design [4]. As a set of reflectors, fibre Bragg gratings (FBG) with required spectral reflection lines can be used, which are attached to the output of an $1 \times N$ single-mode fibre switch whose input is coupled to the narrow-aperture output of the SLD.

Transmitters with a discretely tuned carrier frequency attract great interest due to the rapid development of fibreoptic communication systems with wavelength division multiplexing (WDM). Such a transmitter can be built using the configuration proposed above by using a set of narrow-bandwidth FBGs with a regularly varied wavelengths of the resonant reflection. For example, a set of FBG with a reflection bandwidth of 0.1 nm and a spacing between the adjacent reflection maxima of FBG of 0.2 nm can be used. The spectral tuning of the samples presented above shows that they can be used for fabricating a transmitter with a few tens of frequency channels, each of them having a bandwidth of 100 GHz.

It is important that the given active element can be also used as a travelling-wave amplifier. An estimate of the average single-pass gain of a wave travelling towards the wide-aperture output (the dashed curve in Fig. 2) shows that the gain exceeds 20 dB at high injection currents. It is obvious that the single-pass gain will be slightly above 20 dB in a similar amplification saturation regime and it will be much higher for an unsaturating input signal if the input signal is radiation from a master single-frequency laser tuned to the spectral maximum of the optical gain. Such devices are of interest for spectroscopy. In particular, the maximum of the optical gain of the samples studied in this paper is in a range of the resonant lines of Rb, which makes them promising for the use in atomic beam cooling experiments [5].

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