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Analysis of the emission parameters of low-power superluminescent diodes in the temperature range from $-55\,^{\circ}$C to $+93\,^{\circ}$C

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Abstract. **The main physical parameters of superluminescent diodes are studied in the spectral range 800 – 850 nm and temperature range from $-55\,^{\circ}$C to $+93\,^{\circ}$C for an output power of the order of 0.1 mW. It is shown that such diodes can be used in low-power miniature light-emitting modules that can operate in a wide temperature range without thermal stabilisation of the active element.**

Keywords: *superluminescent diode, light-emitting module, temperature dependences of the output power, spectrum and polarisation.*

1. Introduction

Superluminescent diodes (SLDs), in which the known merits of light-emitting and laser diodes are combined successfully, are being used widely at present in various fields of science and engineering requiring broad-band sources of optical radiation. First of all, these are fibreoptic sensors of different types, including gyroscopes. The use of SLDs as sources of radiation in optical tomography, 'white-light' interferometry, optical reflectometry, etc., where the main requirement on the optical radiation sources is a combination of a high brightness and a broad spectrum (low coherence), is very promising.

In order to stabilise the power, spectral and polarisation parameters of radiation, and to increase the reliability of the devices, SLDs in light-emitting modules are usually mounted on a special microcooler (thermoelectric Peltier element) which makes it possible to maintain the temperature of the diodes during operation at a constant level (usually $20\,^{\circ} - 25\,^{\circ}$C). A typical SLD light-emitting module with an output power of several units or tens of milliwatt has a volume 2 – 3 cm^3, and its power consumption may be up to 5 W at extremal temperatures. The power consumption by the SLD itself is only about 0.3 W in this case.

For most optical sensors, an output power level of the order of 0.1 mW is quite sufficient. Apart from this, weight and size considerations as well as the power consumption by the module are crucial for devices used under field conditions. Cost-reduction is also an important factor. Therefore, the creation of miniature low-power light-emitting modules that can operate in a wide temperature range without thermal stabilisation of the active element is an urgent task. In this paper, we study the main physical parameters of experimental samples of such emitters in the temperature range from $-55\,^{\circ}$C to $+93\,^{\circ}$C.

2. Experimental samples and measuring technique

SLD samples were made of (GaAl)As double heterostructures with separate confinement (SC DHS) grown by the MOCVD method. A mesastructure of width $w = 4$ μm and height of about 2 μm prepared by the ion etching technique provided lateral confinement. It is known that the positive radiation feedback can be suppressed by various methods during the fabrication of SLDs. These include the deposition of an antireflection coating on the diode facets, an inclined position of the active channel (straight or curved) relative to the diode facets, the use of multisectional structures with absorbing regions, disordering of the optical waveguide in the regions adjoining the diode facets, as well as various combinations of these methods [1 – 6].

To minimise back reflection of radiation into the active channel, the axis of the latter was inclined at an angle of 7° to the normal to the crystal facets. In addition, dielectric antireflection coatings ($Al_2O_3 - ZrO_2$ or Al_2O_3) with a power reflection coefficient $R < 1\,\%$ were deposited on both crystal facets. Fig. 1 shows the configuration of the active channel of an SLD. Estimates show that the reflection coefficient for radiation into the active channel does not exceed 0.01 % for such a configuration.

The length L_a of the active channel can be varied over a wide range, thus making it possible to optimise the output characteristics of the SLD. In our investigations, we used SLDs with $L_a = 600$ and 1000 μm.

SLD samples were prepared from SC DHS (active layer thickness 250 Å, waveguide layers of thickness 0.12 μm) with an electroluminescence wavelength in the spectral range 800 – 840 nm. Such heterostructures were used earlier for commercial production of SLD modules, which featured good reliability (long service life), high stability of output characteristics and their reproducibility from sample to sample upon thermal stabilisation ($T = +25\,^{\circ}$C).

The volume of the experimental modules was smaller than 0.4 cm^3. The radiation was outcoupled through single-mode optical fibres (isotropic or PM). An SLD on a heatsink, a butt joint with an end fibre microlens, and a miniature film thermoresistor were mounted in the casing of a module having appropriate electric leads. After adjust-

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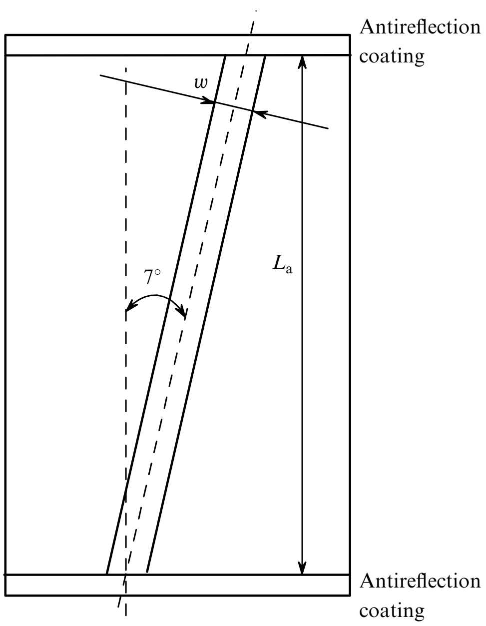

Figure 1. The SLD configuration.

ment and fixation of the fibre, the casing was soldered hermetically.

To measure the temperature dependences, SLD modules were placed in a Mini SubZero MC-81 chamber, the fibres being brought out from the chamber through special thermally insulated holes. The temperature measurements were performed in the range from −55 °C to +93 °C, which is sufficient for most practical applications of SLDs. The modules in the chamber were mounted on a massive heatsink, and the temperature-sensitive element of the chamber was used for a rough setting of temperature. The exact temperature inside the module casings was controlled by inbuilt thermistors.

The injection current in the SLD was set by a stabilised dc source. The output optical power was measured by an ILXOMM-6810B power meter. Corrections for the shift of the central wavelength of the SLD radiation were made in the entire temperature range by measuring the emission spectra of each SLD at each temperature point with the help of an ANDO AQ6371B optical spectrum analyser. For measuring the degree of polarisation, the output radiation was directed to a polariser (Glan prism) through a collimating lens placed in front of it.

3. Experimental results

Figs 2–4 show the temperature dependences of the output power measured for a number of samples. An analysis of a typical family of light–current (L–C) characteristics (Fig. 2) shows that the output power decreases with increasing temperature for a constant injection current. This is quite reasonable in view of the fact that with increasing temperature, the thermal quenching increases and the gain factor decreases for optical transitions between localised states. Qualitatively, the families of L–C characteristics have the same shape for all SLDs with $L_a = 600$ and 1000 μm.

Fig. 3 shows the families of temperature dependences of injection current for SLDs with $L_a = 600$ and 1000 μm, each

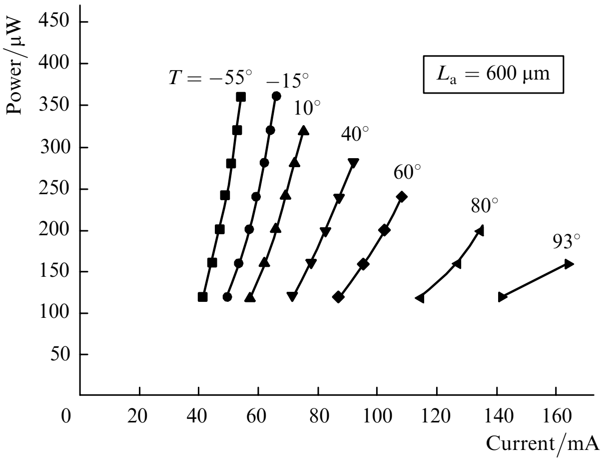

Figure 2. Light–current characteristics of an SLD at different temperatures T ($L_a = 600$ μm).

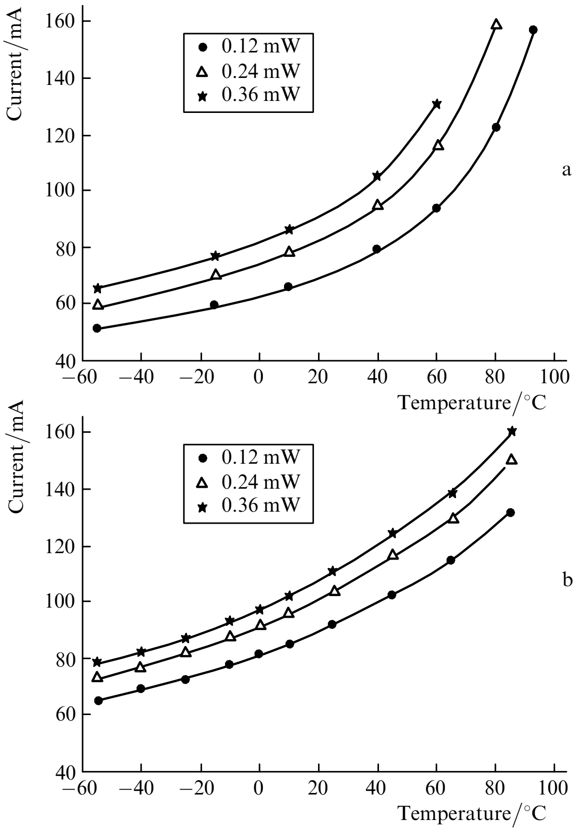

Figure 3. Temperature dependences of the injection currents corresponding to a constant output power; $L_a = 600$ (a) and 1000 μm (b).

curve being characterised by a certain constant output radiation power. One can see clearly that the functions $I(T)$ for $P = \text{const}$ have a stronger temperature dependence for SLDs with $L_a = 600$ μm than for SLDs with $L_a =$ 1000 μm.

Detailed calculations of the temperature dependences of the SLD radiation power parameters were not carried out in this work. However, certain conclusions concerning the observed regularities can be drawn on the basis of simple theoretical models. Generally speaking, a quantitative description of the optical gain, spectral density of the spontaneous emission rate and spectral power density is based on the band structure and matrix elements of the optical transitions. Assuming that the charge carrier concentration is independent of the coordinate, and that the reflection coefficient at the end facets of the emitter is equal to zero, we arrive at the following expression for the spectral density of photons at the SLD output [7]:

$$\varphi_\alpha(\hbar\omega) = \frac{(\Gamma/c_{\mathrm{gr}})R_{\mathrm{sp}}^{(\alpha)}(\hbar\omega)}{\Gamma G_\alpha(\hbar\omega)-\alpha_0}\left[\exp\{[\Gamma G_\alpha(\hbar\omega)-\alpha_0]L_{\mathrm{a}}\}-1\right], \quad (1)$$

where the subscript α corresponds to the TE- or TM-polarisation modes; Γ is the optical confinement factor, c_{gr} is the group velocity of light; $R_{\mathrm{sp}}^{(\alpha)}$ is the spectral density of the spontaneous emission rate; $G_\alpha(\hbar\omega)$ is the gain for optical transitions between localised states; and α_0 are the internal losses.

As the temperature of the SLD increases, the fraction of the induced radiation decreases [the coefficient $G_\alpha(\hbar\omega)$ decreases with temperature, and so does the exponent in Eqn (1)], while the fractions of spontaneous radiation and waveguide losses α_0 increase. Thus, the weaker dependence $I(T)$ will be observed under the conditions $\Gamma G_\alpha(\hbar\omega) \gg \alpha_0$ and $\exp\{[\Gamma G_\alpha(\hbar\omega)-\alpha_0]L_{\mathrm{a}}\} \gg 1$ corresponding to the predominance of stimulated emission. These conditions are satisfied more easily by emitters with a long active channel. In the opposite case, when spontaneous radiation makes a significant contribution to the output power, the dependence under consideration may be stronger.

It should be noted that the dependences presented in Fig. 3 are reproduced quite well from sample to sample. Thus, only two out of more than 50 investigated emitters with $L_{\mathrm{a}} = 600$ μm show 'anomalous' dependences $I(T)$ at low temperatures (Fig. 4). Such an anomalous behaviour of the diodes [described by curves (*2*) and (*3*)] can be due to the anomalous behaviour of the radiation pattern of SLDs at low temperatures [8, 9], as well as to a non-optimal adjustment of its active channel relative to the fibre microlens in the butt joint. Note that the low-temperature region is the most sensitive region from the point of view of sustaining a given level of the output radiation power. The slope of the L−C characteristics increases sharply with decreasing temperature (see Fig. 2), i.e., slight variations in the injection current induce large variations in the output power. For SLD modules used in devices with a feedback loop for maintaining a constant level of the output radiation power, anomalous dependences $I(T)$ for P = const pose no hazards. However, if this dependence is approximated in the control unit by, say, a parabolic law, the anomalous modules cannot be used.

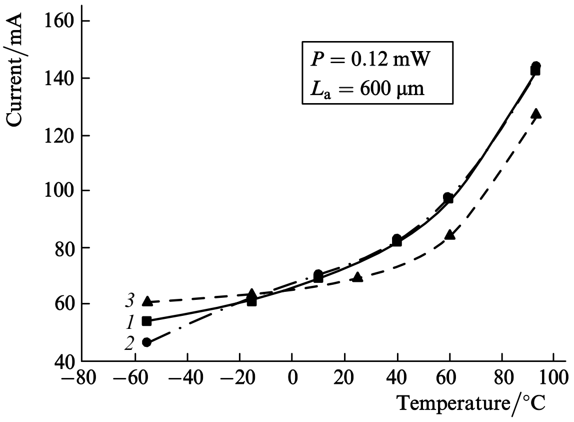

Figure 4. Typical (*1*) and 'anomalous' (*2, 3*) dependences $I(T)$ for three diodes with $L_{\mathrm{a}} = 600$ μm for $P = 0.12$ mW.

The change in the ratio of contributions from spontaneous and stimulated radiation described above is also confirmed by the temperature dependences of the half-width of the spectral lines, which are shown in Fig. 5; the spectral line becomes narrower with decreasing temperature because the gain is higher (and hence the fraction of the stimulated radiation is larger) at low temperatures.

Fig. 6 shows the temperature dependences of the polarisation characteristics of the output radiation of modules with a singlet-mode isotropic fibre and a PANDA fibre retaining polarisation. For the first type of modules, the

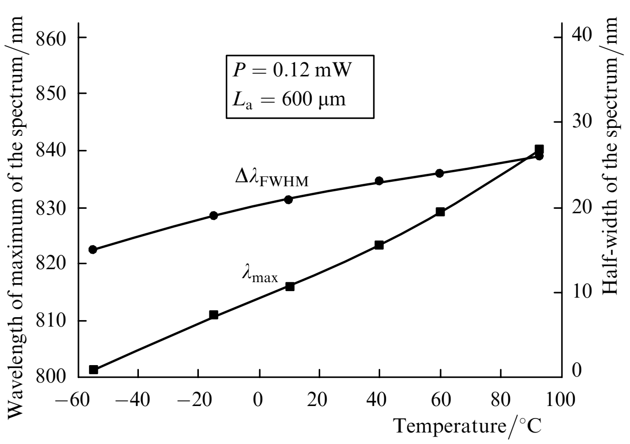

Figure 5. Typical temperature dependences of the maximum λ_{max} and half-width $\Delta\lambda_{\mathrm{FWHM}}$ of the spectrum of an SLD ($L_{\mathrm{a}} = 600$ μm).

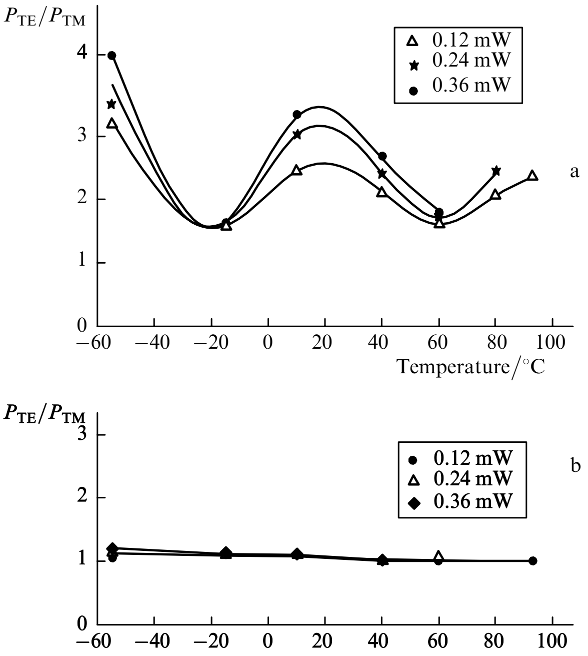

Figure 6. Temperature dependences of the ratio of radiation powers in TE and TM polarisations for modules with an isotropic (a) and anisotropic (b) output fibre for different output power levels.

temperature dependence of the ratio of powers in the TE and TM polarisations is not reproduced from sample to sample. Their common feature is an increase in the value of $P_{\mathrm{TE}}/P_{\mathrm{TM}}$ with increasing output power, which is also a characteristic feature of the SLD themselves. As for the large spread in the form of the dependences $P_{\mathrm{TE}}/P_{\mathrm{TM}}(T)$, it can apparently be attributed to temperature-induced mechanical stresses produced in the butt joint. As a result, the fibre is no longer isotropic and becomes sensitive to polarisation. This circumstance has a strong effect on the corresponding parameters of the output radiation.

Depolarised output radiation can be obtained in modules with a PM single-mode PANDA fibre. Experiments carried out by us reveal that the radiation from such modules remains virtually depolarised (degree of polarisation is less than 10 %) in the entire investigated temperature range (Fig. 6b).

4. Conclusions

Our investigations clearly indicate the possibility of creating a new family of light-emitting SLD modules. These miniature low-power devices (with a maximum power consumption of about 0.3 W) with an output power of about 0.1 W outcoupled through a single-mode fibre are capable of operating in an extremely wide temperature range without thermal stabilisation of the active element. The reliability of such modules is a subject that needs to be studied independently. For similar SLDs operating in thermally stabilised modules, a median lifetime of over 10^5 h has been demonstrated and confirmed regularly [9, 10]. In this case, the service life will depend strongly on the working conditions since the ageing mechanism of SLDs, as well as of all optoelectronic devices, is of activation type. Under conditions of continuous operation at extremely high temperatures, the service life may be reduced by more than an order of magnitude. In the opposite case (at extremely low temperatures), the service life may exceed 10^6 h.

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