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Double-pass superluminescent multilayer quantum-well (GaAl)As heterostructure diodes with a reduced power consumption

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***Abstract*. Superluminescent diodes (SLDs) based on a three-layer quantum-well (GaAl)As heterostructure with a bent active channel emitting in the spectral range from 820 to 840 nm are studied. The diodes can operate without thermal stabilisation in the temperature range between −55 and +93 °C emitting 0.1 mW of optical power at the output of a single-mode fibre. They offer a significant advantage in operating currents and power consumption over conventional SLDs based on a bulk separate-confinement double heterostructure.**

Keywords: *superluminescent diode, multilayer quantum-well structure, bent active channel.*

1. Introduction

The power consumption and size of superluminescent diodes (SLDs) used as radiation sources in fibreoptic sensors of different types, in particular, fibreoptic gyroscopes are their most important technical parameters. SLDs based on a bulk (GaAl)As separate-confinement double heterostructure (SC DH) operating in a broad temperature range without thermal stabilisation were studied in Ref. [1]. These investigations resulted in the development of a light-emitting 381-MiniBut-SM-HT SLD module, which is now manufactured commercially and finds broad practical applications.

To further reduce the power consumption of such modules, we studied SLDs based on (GaAl)As multilayer quantum-well heterostructures (MQWHs). Laser diodes fabricated from such MQWHs have considerably lower threshold currents and a higher external quantum efficiency than lasers based on bulk SC DHs. In addition, to reduce operating currents providing the required output power (∼ 100 μW at the output of a single-mode fibre), we used diodes with a bent active channel instead of conventional SLDs. Such an asymmetric design of the SLD, which was first used in Ref. [2], provides an advantage in the output power and ensures tunable output radiation in a broad spectral range due to controllable double-pass radiation in the SLD [3, 4]. In this paper, we used the first advantage.

2. Experimental samples

We manufactured SLDs from the SC (GaAl)As heterostructure which was grown at low pressure on a MOCVD SIGMOS-130 setup with a horizontal quartz reactor and a rotating graphite holder for substrates. The growth temperature was 770 °C and pressure in the reactor was 60 Torr. Triethyl gallium and trimethyl aluminium were used as sources of the third-group elements. A source of the fifth-group elements was 100 % arsine. Diethyl zinc and monosilane were used as sources of dopants of the p and n types, respectively.

The MQWH is shown schematically in Fig. 1. The active region contains three quantum wells of thickness 8 nm, which are separated by two 4-nm thick barriers. The

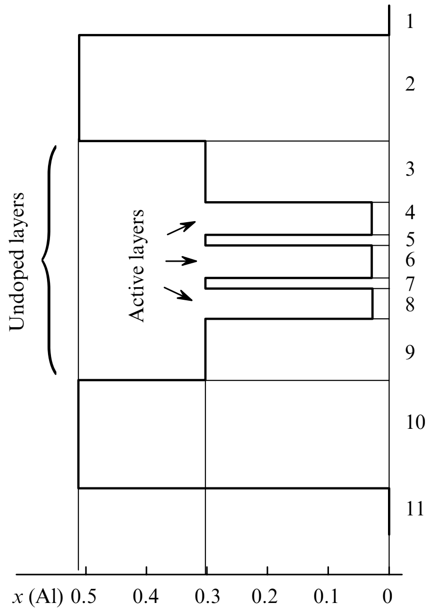

Figure 1. Three-layer quantum-well ($Ga_{1-x}Al_x$)As heterostructure: (1) contact p^+-GaAs layer; (2) ($Ga_{0.49}Al_{0.51}$)As p-emitter; (3, 9) ($Ga_{0.7}Al_{0.3}$)As waveguide layers, $d = 80$ nm; (4, 6, 8) (Ga_xAl_{1-x})As active layers, $d = 8$ nm; (5, 7) ($Ga_{0.7}Al_{0.3}$)As barrier layers, $d = 4$ nm; (10) ($Ga_{0.49}Al_{0.51}$)As n-emitter; (11) n-GaAs substrate.

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thickness of the waveguide layer was 0.19 μm. All the layers were undoped.

The lateral optical confinement of the active channel (width $w = 4$ μm) was provided by a ridge waveguide, which was fabricated by ion etching. The active channel was bent (Fig. 2). Its axis made an angle of 7° with respect to the normal to the front (output) facet of the SLD and was perpendicular to the rear facet. Depending on the position of a cleavage forming the rear facet, the length L_a of the active channel could be varied. The front facet was covered with a multilayer dielectric antireflection coating, which provided the effective reflectivity $R_1 < 10^{-4}$. The rear facet was covered with a broadband dielectric mirror with the reflectivity R_2. We could vary the reflectivity R_2 and the active channel length L_a in experiments to optimise the output parameters of the SLD.

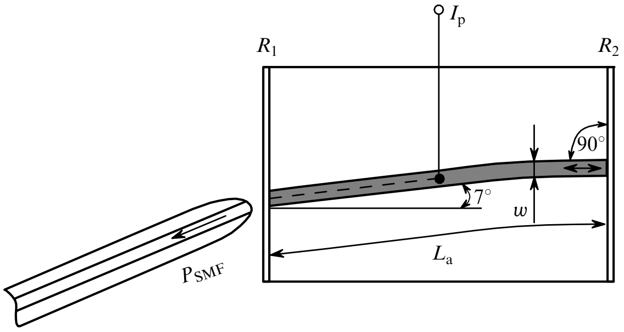

Figure 2. Design of a double-pass SLD with a bent active channel.

It is known that an important technical parameter of an SLD is the depth of the residual periodic modulation of its emission spectrum by the modes of a Fabry–Perot resonator. This quantity depends on the one-pass optical gain ($G_s = \exp\{[g(\lambda) - \alpha]L_a\}$, where $g(\lambda)$ is the optical gain and α is the coefficient of dissipative losses) and the reflectivities of radiation from end facets as

$$m_s = \frac{2(R_1R_2)^{1/2}G_s}{1 + R_1R_2G_s^2}.$$

In the range of variation in G_s realised in practice, the residual spectral modulation is $m_s \sim (R_1R_2)^{1/2}G_s$.

A peculiarity of the SLD considered here is the asymmetric distribution of intensities of the right- and left-travelling light fluxes with a maximum located near the front facet. This provides a higher external efficiency compared to that of conventional SLDs. However, because of the higher values of R_2, the provision of the acceptable values of $m_s \simeq 1$ % becomes a more complicated problem with very strict requirements imposed on R_1. In this paper, these requirements were alleviated because the needed level of the output power was achieved at a rather low optical gain, spontaneous emission being a great part of the output radiation.

Because the SLDs under study were intended for the use in modules from which radiation was coupled out through a single-mode fibre, the SLD design and operating regimes were optimised in measurements at the fibre output (Corning Pure Model HI 780) using a fibre microlens at the input (Fig. 2). The spectral characteristics of radiation were measured with an ANDO AQ 6317B spectrum analyser with a resolution of 0.01 nm. The SLD was optimised by varying the active-channel length L_a and the reflectivity R_2 of the rear facet to obtain the output power $P_{SMF} > 0.1$ mW at a minimum operating current I_p for a relatively broad spectrum ($\Delta\lambda > 10$ nm) with a small residual modulation ($m_s < 3$ %). In this case, the width $\Delta\lambda$ of the spectrum, which determines the degree of the SLD coherence, corresponded to the FWHM of the spectral line $S(\lambda)$. The depth of spectral modulation near the central wavelength λ_c corresponding to the spectral maximum was determined from the expression

$$m_s = \frac{S_{max} - S_{min}}{S_{max} + S_{min}}.$$

To optimise the SLD, we fabricated diodes with the active-channel lengths $L_a = 400$, 600, and 800 μm. The front facets of the SLDs were covered with an antireflection coating and the reflectivities of the rear facets were $R_2 = 0.5$ %, 15 %, 30 %, and 90 %. We measured the light–current characteristics $P_{SMF}(I)$ and emission spectra for $P_{SMF} = 0.12$ mW. Optimal results were obtained for SLD with $L_a = 600$ μm. Typical values of I_p, $\Delta\lambda$, and m_s for $P_{SMF} = 0.12$ mW ($T = +25$ °C) as functions of R_2 are shown in Fig. 3. It follows from Fig. 3 that there is no sense in depositing mirrors with $R_2 > 30$ % on the rear facet because the operating current almost does not decrease in this case, whereas the depth of parasitic modulation of the spectrum noticeably increases.

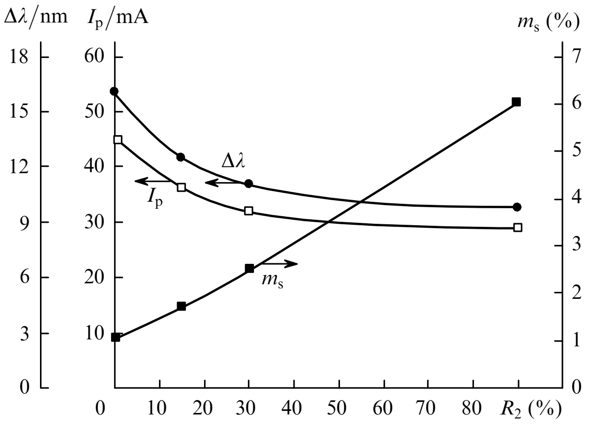

Figure 3. Dependences of the operating current I_p, the half-width $\Delta\lambda$ of the emission spectrum, and the spectral modulation depth m_s on the reflectivity R_2 of the rear facet of the SLD for $P_{SMF} = 0.12$ mW, $L_a = 600$ μm, and $T = +25$ °C.

An additional decrease in the energy consumption for these SLDs is achieved due to a weaker temperature dependence of the emission characteristics of MQWHs compared to bulk SC DHs. Figure 4 shows the typical temperature dependences of operating currents providing $P_{SMF} = 0.12$ mW for three types of SLDs with $L_a = 600$ μm, namely, the conventional 'symmetric' SLD based on a bulk SC DH [1], the SLD of the same design based on the MQWH described above, and the SLD based on the MQWH with a bent active channel ($R_2 = 30$ %).

Dependences $I_p(T)$ clearly demonstrate a significant advantage in the energy consumption for the SLD of the third type. This is especially strongly manifested at high

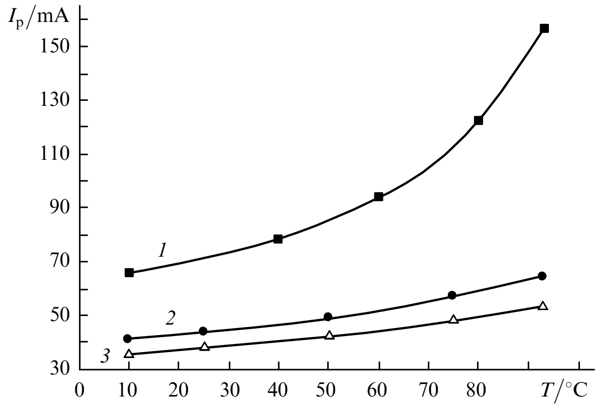

Figure 4. Temperature dependences of operating currents for $P_{\rm SMF} = 0.12$ mW and $L_a = 600$ μm for the conventional SLD based on the bulk SC DH (*1*) and MQWH (*2*) and for the double-pass MQWH SLD with a bent waveguide (*3*).

temperatures of the environment. Thus, the operating current of SLDs of the third type at +93 °C is three times lower than that of conventional SLDs based on a bulk SC DH (and their power consumption is additionally lowered by 20 % – 30 % due to a lower voltage applied to the SLD). Note that the temperature $T = +93$ °C is indicated as the maximum operating temperature in technical specifications of fibre sensors. Such a reduction in the power consumption for SLD modules used under field conditions or among 'densely packed' optoelectronic components is a great advantage. One can see from the curves shown in Fig. 4 that this result was achieved mainly due to the use of the multilayer quantum-well heterostructures.

The problem of reliability of such SLDs requires additional investigations.

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