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Optical loss in strained quantum-well semiconductor ridge lasers

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Abstract. The results of measurements of optical loss in semiconductor ridge lasers are presented. The InGaAs/AlGaAs/GaAs single-quantum-well semiconductor lasers are studied in the spectral range from 1019 to 1042 nm, which corresponds to the long-wavelength wing of the mode gain curve. It is shown that the dominant mechanism of optical loss appears to be light scattering by optical inhomogeneities of the laser waveguide, while the free-carrier absorption is negligible in the lasers studied.

1. Introduction

The development of high-power and highly efficient semiconductor lasers attracts considerable attention at present. Optical loss are one of the most important parameters that determines the ultimate laser characteristics, in particular, its efficiency. Nonresonance absorption and scattering, which contribute to the total loss α, reduce the differential efficiency of the laser. To decrease the threshold current density and to improve the heat removal, it is reasonable to increase the laser length L. However, in this case, α should be decreased to prevent a reduction in the laser efficiency. The understanding of the nature of nonresonance loss and determination of the dominant mechanism (scattering and absorption by free carriers), which contributes to optical loss, allow one to design lasers with improved characteristics.

The aim of this work is to study nonresonance loss and their nature in InGaAs/AlGaAs/GaAs quantum-well injection ridge semiconductor lasers.

2. Experimental

We studied laser diodes with a ridge waveguide (the ridge was 3.5 μm wide). The lasers were fabricated of one heterostructure but had different cavity lengths (200, 400 and 600 μm). The other parameters of the laser diodes are given in [1].

The spectra of amplified spontaneous emission were measured with a computerized setup based on a multichannel spectrum analyzer. The digitized superluminescence spectra obtained in the spectral range 1019 – 1042 nm for different pump current densities (200 – 1500 A cm^{-2}) were used as input data for mathematical processing. The spectral range 1019 – 1042 nm corresponded to the long-wavelength wing of the total mode gain curve. The laser diode gain was found from the ratio of the laser cavity intermode spacing to the width of the resonance at some level, which allowed us to minimise the error caused by the wings of the instrumental function of the spectral setup. The experimental setup and the method for processing the spectra are described in more detail in [1].

Using this method for processing the spectra, we obtained the dependences of the mode gain on the photon energy. Fig. 1a shows the typical curve of the mode gain for the laser with a cavity of length 400 μm for the pump current density of 785.7 A cm^{-2}. The long-wavelength part of the curve, which was studied in more detail, is marked with a circle. Note that the obtained spectral dependence of the total gain G includes the spectral dependence of the mode gain

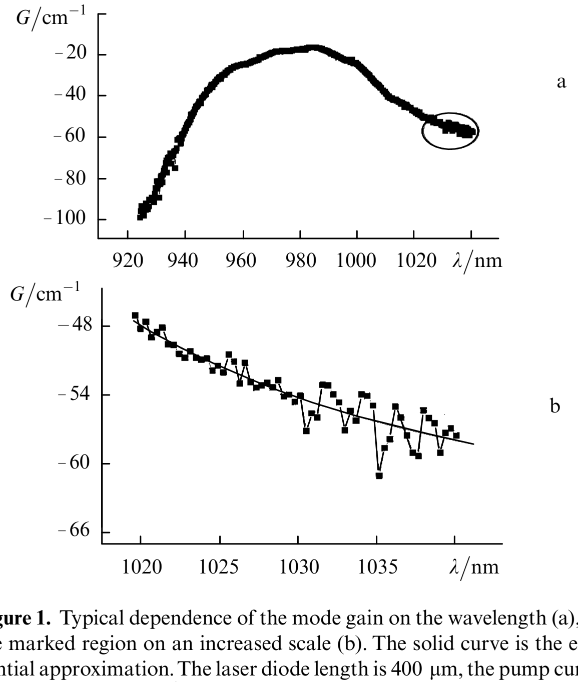

Figure 1. Typical dependence of the mode gain on the wavelength (a), and the marked region on an increased scale (b). The solid curve is the exponential approximation. The laser diode length is 400 μm, the pump current density is 785.7 A cm^{-2}

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G_a in the laser active layer and the optical loss α_{las} caused by absorption and scattering in the passive layers of the structure:

$$G = G_a - \alpha_{las}. \qquad (1)$$

The long-wavelength parts of the mode gain curves in the spectral range from 1019 to 1042 nm were approximated by an exponential. The typical long-wavelength tail for the laser diode with the cavity length 400 μm for a current density of 785.7 A cm^{-2} is shown in Fig. 1b. To obtain the spectral dependence of the internal loss for different lasers, we assumed that the parameter α in the expression for the loss in the laser

$$\alpha_{las} = \alpha + \frac{1}{2L}\ln\frac{1}{R_1R_2} \qquad (2)$$

is the same for all the lasers (here, R_1 and R_2 are the reflectivities of laser cavity mirrors). From the values of α_{las} for three laser diodes, we calculated the average coefficient $b = {}^1/_2 \ln(1/R_1R_2)$ equal to 1.6 (with the error of 10%). Assuming that the spectral dependence of the total gain G in the long-wavelength range is mainly caused by the optical loss α_{las}, we obtain

$$\alpha = -G - \frac{b}{L}. \qquad (3)$$

Using this method, we obtained the dependence of the internal loss on the wavelength for different pump current densities for all the lasers.

Fig. 2 shows the spectra of the internal loss for the lasers with the cavity lengths of 200 and 400 μm. One can see that optical loss strongly depend on the wavelength, the dependence changing with the laser cavity length. The curves for the laser with the cavity length 600 μm are similar to those shown in Fig. 2, but have a weaker spectral dependence.

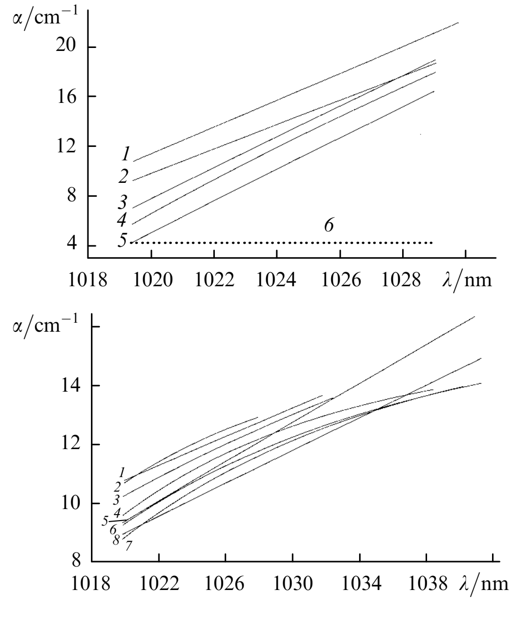

Figure 2. Exponentially approximated spectral dependences of optical loss for a sample with $L = 200$ μm for the current density 714.3 (*1*), 857.1 (*2*), 1000 (*3*), 1142.9 (*4*) and 1285.7 A cm^{-2} (*5*) and the dependence *6* calculated by expression (*4*) (a), and analogous dependences of optical loss for a sample with $L = 400$ μm for the current density 285.7 (*1*), 357 (*2*), 500 (*3*), 571.4 (*4*), 642.8 (*5*), 714.3 (*6*), 785.7 (*7*) and 857.1 A cm^{-2} (*8*) (b).

The decrease in α with increasing pump current density appears to be related to the long-wavelength tail of the gain which still contributes to the gain in this spectral range. The data presented in Fig. 2a demonstrate the most strong spectral dependence.

3. Results and discussion

The analysis of the data obtained reveals the two features of optical absorption.

(i) The spectral dependence of the optical absorption is unexpectedly strong in the long-wavelength tail of the emission line. Indeed, according to the conventional concept about the dependence of the optical gain (absorption) on the wavelength, in the long-wavelength region one approaches the transitions corresponding to the bottom of the conduction band and the top of the valence band, where the density of the electronic states tends to zero in a bulk semiconductor or abruptly vanishes in the case of a two-dimensional quantum well.

At first sight, the contribution of these transitions to the optical gain also tends to zero with increasing wavelength. In this case, the optical loss should tend to a constant value, which is determined by the nonresonance loss or the free carrier absorption.

However, it follows from Fig. 2 that the loss increase with the wavelength and decrease with increasing the pump current density rather than increase, as it would be upon absorption by free carriers. Fig. 2a shows the curve of optical loss α calculated by formula (4) and extrapolated from the short-wavelength side of the spectrum to its long-wavelength side assuming that the loss are caused by the free carrier absorption. In this calculations, we set $\alpha_0 = 4.23$ cm^{-1} at the wavelength $\lambda_0 = 1019.36$ nm for the current density of 1285.7 A cm^{-2}, and performed extrapolation to the long-wavelength side using the expression

$$\alpha = \alpha_0\left(\frac{\lambda}{\lambda_0}\right)^3, \qquad (4)$$

which is in principle valid for the free carrier absorption and gives the strongest spectral dependence.

Fig. 2a shows that even the strongest spectral dependence ($\sim \lambda^3$) of the absorption coefficient of light by free carriers chosen by us looks like as almost a constant function in the spectral range under study. Thus, it is obvious that the free carrier absorption virtually makes no contribution to the observed spectral dependence.

(ii) The initial spectral dependence of optical loss at the long-wavelength wing has a distinct fluctuation character (Fig. 1b). This is also manifested in the data shown in Fig. 2, where a nonregular behaviour of the interpolated curves points to a stochastic character of the loss mechanism. This mechanism can be only scattering by inhomogeneities of the laser waveguide. One can see from Fig. 1b that the loss are in the range of 1 – 5 cm^{-1}. The conclusion about the substantial effect of optical scattering on optical loss in the cavity has been also made in [2 – 4]. The specific spectral behaviour of fluctuations of optical loss is related to the spatial distribution of scattering inhomogeneities along the axis of the laser cavity [3].

Although it is commonly accepted that the free carrier absorption gives the dominant contribution to the nonresonance loss in a semiconductor laser [5], the results of this paper and of papers [2 – 4, 6] suggest that this contribution is not dominant in typical semiconductor lasers.

Returning to the strong spectral dependence of optical loss, we can suppose that such a behaviour of α calculated by formula (3) is related to the gain G_a in the active layers rather than to optical loss in the passive layers. This is confirmed by the decrease in α with increasing pump current density in this spectral region. It is likely that we deal with the case when the shape of the homogeneous line differs substantially from Lorentzian or Gaussian shapes due to the existence of a broad pedestal or wings, which spread far away from the line centre.

The complicated shape of the homogeneous line of the interband transition in an active medium of semiconductor lasers was noted early in [7 – 9]. Because of the existence of broad wings of the homogeneous line, the electronic transitions corresponding to the photon energies near the maximum of the spectral mode gain curve will also contribute to the gain in the long-wavelength part of this curve. As a result, the long-wavelength wing can get the spectral dependence and the dependence on the pump current (see Fig. 2).

4. Conclusions

The results of our work show that the dominant mechanism of optical loss appears to be the light scattering by optical inhomogeneities of the laser waveguide, whereas absorption by free carriers plays no substantial role in semiconductor lasers studied. The conclusion is most encouraging because it seems that the restrictions imposed on the use of lasers of this type with long cavities are related not to fundamental physical mechanisms such as absorption of light by free carriers, but to the technological problems of the sample quality.

One can hope that the improvement in the technology of fabrication of heterostructures, namely, the refinement of the quality of boundaries in heterostructures and the reduction of fluctuations of their composition will result in a decrease in optical loss caused by scattering. In turn, it will allow one to use lasers with longer cavities that produce higher output cw powers.

Note also that our results show that the homogeneous line has a complex shape. It is the existence of broad wings of the homogeneous line that can explain the observed behaviour of the mode gain in its long-wavelength edge. However, to interpret the available data conclusively, additional experiments are required. In particular, one should study the effect of spatially nonuniform pumping of the active region (in the plane of the $p-n$-junction along the laser ridge) on the spectral profile of the mode gain. Although we attempted to decrease this effect, we failed to eliminate it completely.

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