Selection of the lasing frequency and heating the quantum-well heterostructure laser diodes

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Abstract: Numerical simulation of controlling the lasing frequency for the 1.5 µm-range quantum-well heterostructure laser diodes is developed with taking into account increasing the active region temperature under pump current modulation. Peculiarities of the amplitude-frequency characteristics are analyzed at selection of the lasing frequency. General description of the heating of the laser active region during the current modulation is given and selection conditions of the lasing frequency that provide the response bandwidth up to 40 GHz are established.

To solve some scientific and practical tasks there are required dynamic single-frequency semiconductor lasers with narrow and stable radiation line [1, 2]. Besides, in a number of cases it is necessary to tune the lasing radiation frequency within the gain band. In particular, an important interest is a systematic research of output parameters of semiconductor lasers with a high-frequency pump current modulation and selection of the lasing frequency, which is used in fiber-optical information systems [3, 4]. One from the main problems of fiber-optical communication with wavelength-division multiplexing is development of laser emitters with line of width no more than 0.1 nm and maintaining the modulation signals with frequencies up to 10 GHz. To such a requirement there are the most suitable semiconductor lasers with an external Bragg fiber grating on single-mode waveguides [1].

In the work, using numerical modeling the amplitude–frequency characteristics and resonance properties of the response of semiconductor lasers emitting in the diapason of 1.5 µm are investigated. These emitters based on the quantum-well (QW) GaInAs–GaInAsP heterosystem are the principal sources for fiber-optical communication networks. As shown, at typical laser diode parameters due to spectral selectivity it is possible in the range of 1.5 µm to extend and get the modulation response bandwidth up to $\approx$ 40 GHz [4].

At first, discuss a problem of change in the active region temperature under pump current modulation. By definition, a heating of the active region is equal to

$$\Delta T = R_T s W_T,\qquad(1)$$

where R_T is the thermal resistance, s is the contact square, W_T is the dissipated thermal energy per unity square of p–n junction. In general, we have (in W/cm^2)

$$W_T = R_0 j^2 + \frac{\eta' h \nu_{st}}{e}\left((1-F)j + Ff(j)\right).\qquad(2)$$

Here, $R_0 j^2$ determines physical irremovable cause of heating, *i. e.*, Joule heating, the function $f(j)$ characterizes conditions of pumping the semiconductor source active region and

$$f(j) = j_{th} + \gamma(j - j_{th}) = j_{th} + \left(1 - \frac{\eta_{st}}{\eta'}\right)(j - j_{th}).\qquad(3)$$

A threshold current density is j_{th}, the parameter $\gamma = 1 - \eta_{st}/\eta'$ shows the part of the pump current above the threshold that is uselessly spend, η_{st} is the internal quantum yield of lasing, η' is the injection efficiency. Output function of a laser with the Fabry–Pérot type cavity equals $F = k_r/k_l = k_r/(k_r+\rho)$, where $k_r = (1/2l)\ln(1/r_1 r_2)$ is the useful output losses, $k_l = k_r + \rho$ is the cavity loss coefficient, ρ is the internal optical losses, l is the cavity length, r_1 and r_2 are end reflectance.

Substituting (2) and (3) into (1), we obtain [5]

$$\Delta T = R_T s\left(R_0 j^2 + \frac{\eta' h \nu_{st}}{e}\left(\left(1 - \frac{\eta_{st}}{\eta'}F\right)j + \frac{\eta_{st}}{\eta'}Fj_{th}\right)\right).\qquad(4)$$

Expression (4) has general character and it takes into account practically all the most important mechanisms and processes resulting in heating the active region of an injection laser or light-emitting diode. For a light-emitting diode we have $\eta_{st} = 0$, $F \approx 0$, $h\nu_{st} \rightarrow h\nu \approx E_g$ and therefore

$$\Delta T = R_T sj\left(R_0 j + \frac{\eta' h \nu}{e}\right).\qquad(5)$$

For a laser at the threshold ($j = j_{th}$) we have

$$\Delta T = R_T sj_{th}\left(R_0 j_{th} + \frac{\eta' h \nu_{st}}{e}\right).\qquad(6)$$

In the general case, it has to account a dependence of the threshold on the active region temperature. In pulse regime one has to consider the threshold to be constant and for determining the laser active region temperature it is possible to use expression (4), where the ratio $j/j_{th} = j_b/j_{th}$ is the threshold number (ratio of the direct current component to the threshold).

Typical values of the thermal resistance are $R_T = 30 \div 120$ K/W. To evaluate Joule heating let us use a value of the specific resistance of $R_0 = R_s s = 10^{-4}\,\Omega\,cm^2$, where R_s is the series electrical resistance of the diode (at $s = 5\times10^{-5}\,cm^2$, $R_s = 2\,\Omega$). The thermal resistance value is assumed to be of $R_T = 40$ K/W. Mention ones more that thermal task is rather complex problem and it requires accounting a concrete structure of the laser device and conditions of pumping and of radiation output.

For determining, calculations are developed for dynamical single-mode QW heterolasers in the GaInAs–GaInAsP system having in the active region two QWs of width each ≈ 5 nm. It is considered that lasing occurs at a single longitudinal mode with the frequency ν_{st}, which can to displace at any point of the gain band. To describe operation of the laser, use the rate equation system for the photon density S in the cavity and for the nonequilibrium current carrier concentration N, similarly to [4], *i. e.*,

$$\dot{S} = v\mu(\Gamma k(\nu_{st}) - k_1)S + \beta N_a R_{sp} , \qquad (7)$$

$$\dot{N} = \eta' j/edN_a - R_{sp}/\eta_{sp} - v\mu\Gamma k(\nu_{st})S/N_a , \qquad (8)$$

where v is the light velocity in the active region, μ is the coefficient of fulfillment of the active medium by cavity, Γ is the confinement factor, $k(\nu_{st})$ and k_1 are coefficients of gain and losses, R_{sp} is the rate of spontaneous radiative recombination, β is the coefficient determining the contribution part of spontaneous radiation into lasing mode, j is the pump current density, d is the thickness of the active layer (QW width), N_a is the number of QWs in the active region, η' is the injection efficiency, η_{sp} is the quantum yield of luminescence. The gain spectrum $k(\nu_{st})$ and rate of spontaneous radiative recombination R_{sp} are determined in the framework of the optical model of the active medium with no the **k**-selection rule on the electron wave vector for ground transitions [3, 4].

Modulation of pump current is described in the form, as $j = j_b + j_m\sin(2\pi\nu_m t)$, where j_m and ν_m are depth and frequency of modulation, and j_b is the direct current constant component. It is defined that $j_b = x_b j_{th}$ and $j_m = x_m j_b$, where x_b and x_m are variable parameters, $j_{th} = edN_a R_{sp-th}/\eta'\eta_{sp}$ is the stationary threshold, R_{sp-th} is the threshold rate of spontaneous recombination.

At calculations, there are determined for the GaInAs–GaInAsP system the following parameter values, *i. e.*, $d = 5$ nm, $N_a = 2$, $\Gamma = 0.845 \times 10^{-2}$, $\beta N_a = 10^{-5}$, $k_1 = 25$ cm^{-1}, $\mu = 1$, $\eta_{st}F/\eta' \approx 0.6$. Values of the effective masses m_c, m_{vh}, m_{vl}, m_{vht}, and m_{vlt}, of parameters of heterostructure components and, respectively, of the subband levels E_{c1}, E_{vh1}, and E_{vl1} are found based on some published data (*e. g.*, [2]). In particular, we determine initial quantities, as $m_c/m_e = 0.041$, $m_{vh}/m_e = 0.31$, $m_{vl}/m_e = 0.040$, $m_{vht}/m_e = 0.052$, and $m_{vlt}/m_e = 0.12$. Then, we obtain $E_{c1} = 69.7$ meV, $E_{vh1} = 27.0$ meV, and $E_{vl1} = 88.4$ meV, and the initial transition photon energy is $h\nu_1 = E_g + E_{c1} + E_{vh1} = 815$ meV ($\lambda_1 = 1.5$ μm), where the energy gap at room temperature is $E_g = 718$ meV. In the temperature interval from 300 to 400 K we have approximately (in eV) $E_g(T) = 0.718 - 3.776 \times 10^{-4}(T - 300)$. Therewith, the probability of optical transitions follows a law $A(T) = A_0 - 4.454 \times 10^{-6}(T - 300)$, where at room temperature $A_0 = 4.35 \times 10^{-3}$ cm^2/s.

The threshold data are determined as follows. By means of a selection we find such a quasi-Fermi level difference ΔF_{th} that at a some point ν_{st} of the gain band the certain condition for the maximum gain coefficient with no lasing is fulfilled, *i. e.*, $\Gamma k(\nu_{st}) = g_{hm}(\nu_{st}) = k_1$ (see Fig. 1). After calculations of R_{sp-th},

the threshold current density is received. For the studied system, near the gain spectrum center we obtain (at room temperature) $h\nu_{th} = 831$ meV, $\Delta F_{th} = 848$ meV, and $j_{th} \approx 494$ A/cm^2 (at $\eta' \approx 1$ and $\eta_{sp} \approx 1$).
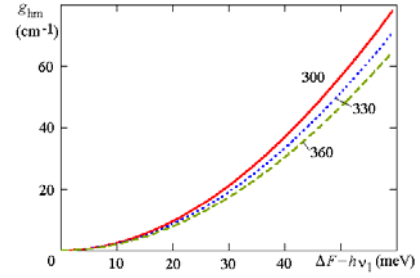

Fig. 1. Dependence of the maximum modal gain g_{hm} on the quasi-Fermi level difference ΔF in the active region. Numbers at the curves are operation temperature (K).

When selecting the lasing wavelength within the gain band the threshold quasi-Fermi level difference ΔF_{th} in the active region follows a specific law (Fig. 2). Results for j_{th} obtained in Fig. 3 were predicted earlier in [6] and demonstrated for the selectively tunable GaSb-based QW laser diodes in [7].
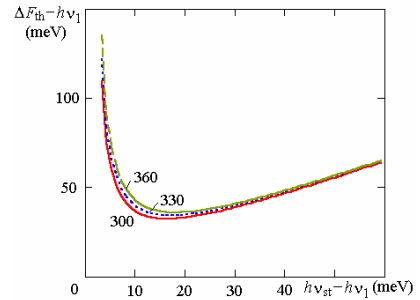

Fig. 2. Dependence of the threshold quasi-Fermi level difference ΔF_{th} in the active region on the displacement of lasing frequency ν_{st} within the gain band. Numbers at the curves are operation temperature (K).
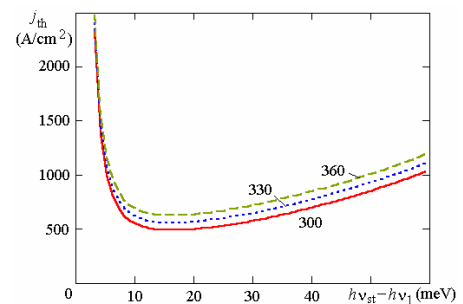

Fig. 3. Change in the density of threshold current j_{th} versus selection of lasing frequency ν_{st} within the gain band. Numbers at the curves are operation temperature (K).

Numerical calculations versus operation temperature are produced using the following obtained expressions for quantities of electron and hole chemical potentials, *i. e*,

$$\zeta_c(\Delta,T) = 79.227 + 7.626 \times 10^{-2}(T-300)$$
$$+ \left(0.584 + 0.013 \times 10^{-2}(T-300)\right)(\Delta - \Delta_1), \qquad (9)$$

$$\zeta_h(\Delta,T) = 17.473 - 7.626 \times 10^{-2}(T-300)$$
$$+ \left(0.416 - 0.013 \times 10^{-2}(T-300)\right)(\Delta - \Delta_1). \qquad (10)$$

Obviously, the sum $\zeta_c + \zeta_h$ is equal to Δ, where $\Delta_1 = 96.7$ meV corresponds to starting the transitions between the first (ground) electron subband and ground heavy hole subband and $\Delta_2 = 158.1$ meV corresponds to starting the transitions between the electron and light hole subbands

General results of the numerical simulation show that changes in direct pump current component, modulation frequency, and in displacement of lasing line within the gain band exert comparatively strong influence on temporal and energy parameters of emission in QW heterolasers. As seen from Fig. 4, if selection occurs at the long-wavelength edge of the gain band ($h\nu_{st} < 0.83$ eV), the heating at the number of threshold of the order of 8–10 reaches up to 12 K. Therewith, the maximum gain coefficient moves (from 1.49 μm to 1.52 μm) towards the lasing wavelength and response characteristics become more improved. The heating at pump current modulation in the case of initial selection of the lasing frequency near the center of the gain band deteriorates the response characteristics because the lasing wavelength deviates from optimal conditions. The worse conditions occur at the short wavelength edge of the gain band ($h\nu_{st} > 0.83$ eV), where the heating can be also of 10 K but the maximum gain coefficient is more shifted, as compared the lasing wavelength, and therefore response characteristics deteriorate.
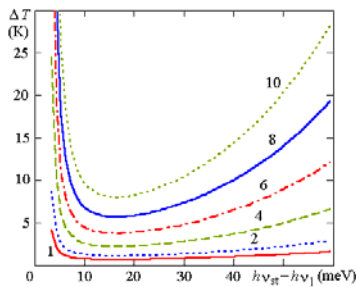

Fig. 4. Growth of the active region temperature ΔT versus selection of the lasing frequency ν_{st} within the band gain and the number of threshold (figures at the curves). Curve 1 is related to initial conditions at room temperature.

Maximum values of the response bandwidth ν_{-3dB} occur at the central part of the gain band. Therewith, increase of the direct current component influences due to heating on quantity of ν_{-3dB} and results in shifting the corresponding ν_{st} into the high-frequency region. At the used system parameters the maximum value ν_{-3dB} reaches of ≈ 40 GHz (Fig. 5). The laser amplitude-frequency characteristics at definite parameters display two local maxima. Low-frequency maximum corresponds ordinary to sub-harmonic 1/2, and high-frequency one to the main resonance [4]. Mention that at a powerful

excitation, where heating is essential, the modulation depth of output radiation changes versus the modulation frequency ν_m.
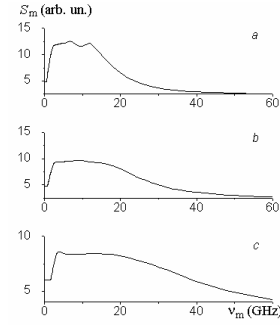

Fig. 5. Amplitude–frequency characteristics $S_m(\nu_m)$ of a laser, (*a*) $h\nu_{st} = 824$, (*b*) 831, and (*c*) 844 meV, $x_b = 10$, $x_m = 1$.

In conclusion, influence of tuning the lasing frequency and of heating on the response of the QW GaInAs–GaInAsP laser diodes is examined in detail. Established features are applied at development of effective optical information systems.

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