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Simulation of Carrier Heating Induced Picosecond Operation of GaInAsP/InP Laser Diode

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Abstract

A self-consistent model of a single-frequency GaInAsP/InP laser diode under carrier heating conditions is presented. The problem is formulated using the rate equations approach to the coupled carrier-phonon-photon system and includes a priori all important interaction processes. The carried out simulation shows the efficiency of a carrier heating induced high-speed modulation.

In the recent years it has been well established that carrier heating effects play an important role in determining the behaviour of laser diodes (LD) and especially their picosecond dynamics. This is due to a strong gain and losses dependences on the carrier temperature [1], while the latter usually relaxates at the picosecond time scale [2]. The phenomenon is of particular significance in the case of single-frequency long-wavelength GaInAsP/InP LD [3], those seem now to be most promising light sources for long-haul optical fiber communications [4]. Here we present the self-consistent model of a such LD and use it for investigation of their high-speed operation induced by carrier heating.

Very fast (during a time less than 0.1 ps [2]) thermalization of a dense electron-hole plasma (EHP) into the active region (AR) of a LD allows to suppose the energy distribution $f(\varepsilon)$ for each sort of carriers as a quasi-equilibrium at any actual time scale, i. e. to write: $f(\varepsilon) = [\exp(\varepsilon/T_e - \xi) + 1]^{-1}$, where T_e is the common effective temperature (measured in energetic units); ε and ξ are the energy and the chemical potential (normalized to T_e). When this distributions is postulated, the objective is to give the consistent discription of a LD's behaviour in terms of ξ and T_e. To solve the problem we use the model [3,5...7] based on the treatment of a LD as a coupled system of nonequilibrium carriers, LO-phonons and guided photons. Under the homogeneous approximation for EHP into the AR it reduces to four rate equations describing the temporal evolution of 1) EHP concentration N_e; 2) EHP energy density E_e; 3) LO-phonon occupation number N_{LO} and 4) effective photon concentration of an excited mode (with a frequency ω) N_ω:

$$\frac{dN_e}{dt} = \frac{J}{e \cdot d} - R_S - R_A - \gamma \cdot v_\omega \cdot N_\omega \ , \qquad (1)$$

$$\frac{dE_e}{dt} = \frac{Q}{d} - W_{LO}\{N_{LO}\} - W_S + W_A + \eta_\omega \cdot v_\omega \cdot N_\omega \ , \qquad (2)$$

$$\frac{dN_{LO}}{dt} = \nu_e \cdot (N_{LO,e} - N_{LO}) - \nu_d \cdot (N_{LO} - N_{LO,o}) \ , \qquad (3)$$

$$\frac{dN_\omega}{dt} = \beta_S \cdot R_S - (\alpha_\omega - \gamma_\omega) \cdot v_\omega \cdot N_\omega \ . \qquad (4)$$

Here, J is the pumping rate per unit volume, Q is the energy flux density flowing into (out of) the AR, R_S and R_A are spontaneous and Auger recombination rates, W_S and W_A are changing rates of the EHP energy due to these processes, W_{LO} is LO-phonon induced energy relaxation rate, $N_{LO,e}$ and $N_{LO,o}$ are LO-phonon Plank's functions with temperature equal to the EHP effective temperature T_e and equilibrium temperature T_o, ν_e and ν_d are LO-phonon emission and decay frequencies depending on the EPH parameters and LA-phonon temperature (equal to T_o) respectively, β_S is the spontaneous emission factor, γ_ω and α_ω are modal gain and common losses coefficients, v_ω is the group velocity of an excited mode, factor η_ω determines the include of an excited mode into the EHP energy changing due to electron-photon interactions.

Basic assumption and detailes of the model one can find elsewhere [3,5..7]. Here we only emphasize, that these rate equations result from the Boltzmann-like equations approach to a coupled carrier-phonon-photon system of a LD, which includes a priori any interaction processes into the AR. To describe these processes we employ the four-band Kane's model and the usual quasi-particle scattering theory.

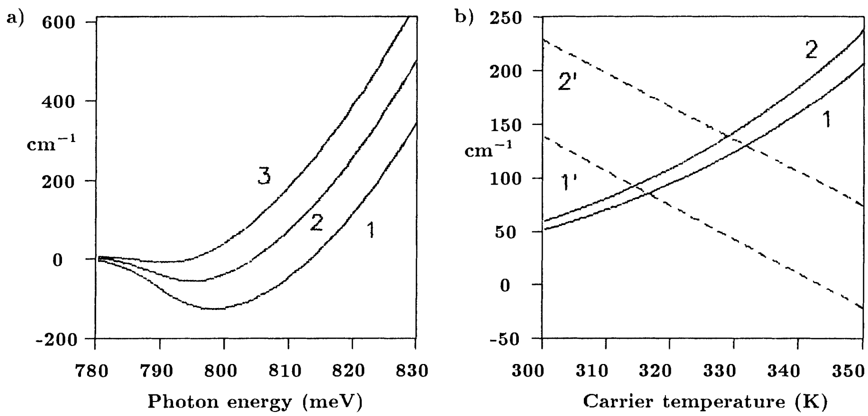

Figure 1: Absorption/gain coefficients. a) - Interband absorption/gain spectra. $N_e = 1.05 \cdot 10^{18} cm^{-3}$. T_e = 300K (1); 325K (2); 350K (3). b) - Peak gain (dashed) and free-carrier absorption (solid). $N_e = 1.05 \cdot 10^{18} cm^{-3}$ (1,1'); $1.20 \cdot 10^{18} cm^{-3}$ (2,2').

First, we examine the carrier heating affect on CW operation of a GaInAsP/InP LD (all presented numerical results correspond to a single-frequency 1.55 μm laser with d = 0.1 μm, $\beta_S = 2 \cdot 10^{-4}$ and material parameters adopted from [8]; the only one free parameter is the LO-phonon decay time $\tau_{LO,d} \sim$ 10 ps [9]). As an example of the calculated data the interband absorption/gain and intraband absorption coefficients are shown in Fig. 1. As it may bee seen from those results the main effects induced by carrier heating are: interband gain suppression (due to degeneracy decreasing) and intraband free-carrier losses (due to intervalence band absorption) activation. Both of them lead to saturation of a light-current curve (see Fig. 2 a)) and give rise to a pump dependence of EHP parameters over the lasing threshold. It must be mentioned, that the latter phenomenon is impossible in the case of a LD with isothermal EHP, but leads to essentually nonlinear behavior of lasing under carrier heating conditions. In particular, it causes a significant CW wavelength chirp of a single-frequency DFB laser (see Fig. 2, b)).

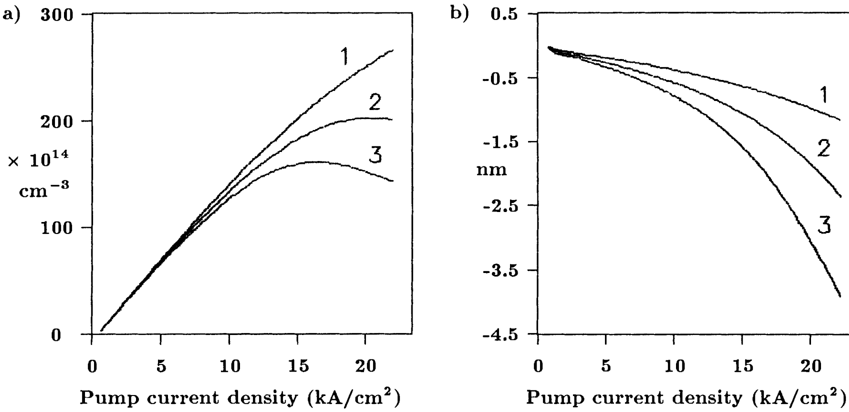

Figure 2: CW characterization. $\tau_{LO,d}$ = 3 ps (1); 6 ps (2); 9 ps (3).
a) - Effective photon density N_ω. b) - Wavelength of generation λ.

Second, we determine the small-signal modulation response of a such laser. There are two different methods for direct modulation under carrier heating conditions. We can do this changing (i) the pump rate J and/or (ii) the energy flux Q coming into an AR. Taking $J = J_0 + \delta J(t)$, $Q = Q_0 + \delta Q(t)$, where $|\delta J| \ll J_0$, $|\delta Q| \ll Q_0$, we'll obtain in a usual way two types of a frequency f response for any modulated parameter A, $\mathcal{M}_J^A(f)$ and $\mathcal{M}_Q^A(f)$:

$$\mathcal{M}_J^A(f) = \frac{\delta A(f)/\delta J(f)}{\delta A(0)/\delta J(0)}\ , \ \mathcal{M}_Q^A(f) = \frac{\delta A(f)/\delta Q(f)}{\delta A(0)/\delta Q(0)}\ . \tag{5}$$

Typical calculated results, presented the intensity and wavelength responses of a GaInAsP/InP single-frequency DFB laser, are shown in Fig. 3. It's clear from these data (see Fig. 3, a)) the bandwidth expansion and nonmonotonous pump dependence of the relaxation-oscillation peak, all caused by carrier heating. Also the strong carrier temperature sensitivity of a DFB laser generation wavelength λ may be seen if one compares $\mathcal{M}_J^\lambda(f)$ (solid lines) and $\mathcal{M}_Q^\lambda(f)$ (dashed lines) curves, presented in the Fig. 3, b).

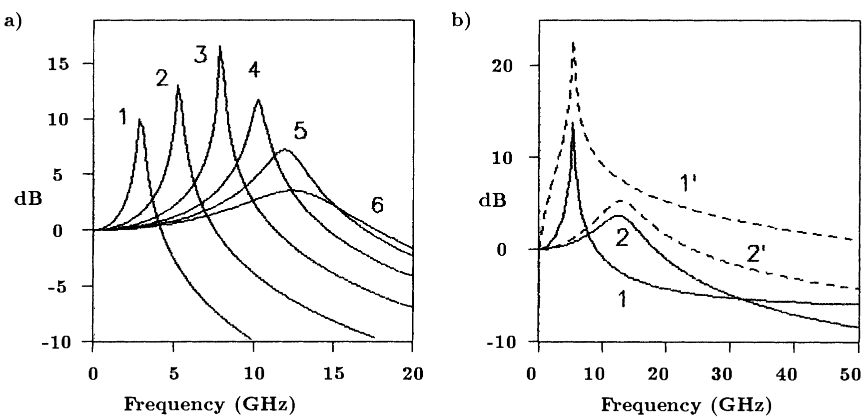

Figure 3: Small-signal modulation response. $\tau_{LO,d}$ = 6 ps. a) - Intensity response. J_0 = 1.1 kA/cm² (1); 1.7 kA/cm² (2); 3.1 kA/cm² (3); 5.0 kA/cm² (4); 7.3 kA/cm² (5); 10.2 kA/cm² (6). b) - Wavelength response. J_0 = 1.7 kA/cm² (1,1'); 10.2 kA/cm² (2,2').

Third, we investigate the large-signal modulation response of a considered LD. In particular, the dynamics under pumping by a sequence of a very short pulses with a duration less than any actual relaxation processes is simulated. Since the shape of a such short pulses makes no differences we suppose them to be δ-shaped and write temporal dependence of a pumping rate J(t) and energy flux Q(t) as:

$$J(t) = J_0 + ed \cdot \mathcal{N}_e \cdot \sum_{(i)} \delta(t - t_i) \ , \ Q(t) = Q_0 + d \cdot \Delta \cdot \mathcal{N}_e \cdot \sum_{(i)} \delta(t - t_i) \ . \qquad (6)$$

Here $\mathcal{N}_e$ is a single pulse induced jump of the EHP concentration N_e, Δ is a surplus energy introduced by a single injected electron-hole pare, t_i is the time for i-th pulse supply (interpulse time is supposed to be large compared to pulses duration). The most interesting for the high-speed operation is the case $\Delta \gg T_e$, i.e. generation of hot carriers, when an appropriate level of the carrier temperature modulation may be achieved without any significant carrier concentration changing. As a result the LD's response is mainly due to carrier temperature (than concentration) modulation and has a speed determined by an effective temperature relaxation time. In Fig. 4 we show the calculated time-dependent response of a GaInAsP/InP single-frequency LD excited by a periodic sequence of a δ-shape optical heating pulses like (6) with a period $\tau = 5$ ps and a surplus energy $\Delta \sim 500$ meV. One can see, that after a few pulses the LD comes to a regime when intensity response with a modulation depth $\sim$ 10 dB repeats with a picosecond sequence of heating pulses.

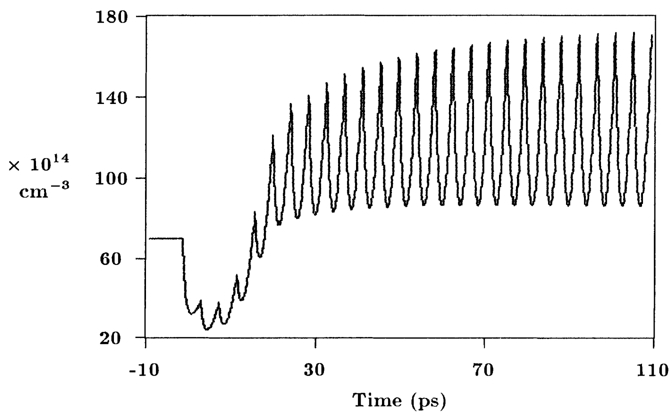

Figure 4: Large-signal modulation response.

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