Effect of Carrier Heating on Static Linearity of MQW InGaAsP/InP Lasers

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Abstract— **Carrier heating can degrade the linearity of the light–current (L–I) characteristics of a laser diode, which is a critical parameter for devices used in cable television (CATV) systems. On the basis of experimental estimation of the carrier heating rate above threshold, we consider the contributions of different mechanisms through which carrier heating can cause static nonlinearity. Comparison with measured L–I characteristics shows that the contribution of carrier heating to L–I nonlinearity is considerably less than previously estimated [1]. We conclude that the carrier heating effect is not a dominant mechanism in producing the intermodulation distortions.**

Index Terms—**Carrier heating, CATV lasers, intermodulation distortions.**

I. Introduction

THE MOST critical parameters determining the performance of cable television (CATV) lasers are slope efficiency, L–I curve linearity and noise level. The noise level in CATV systems is typically limited by two components: shot noise of the laser itself and multipath interference (MPI) in the fiber transforming the laser phase noise into amplitude noise [2]–[5]. While the shot noise is determined by the optical power and has a fundamental nature, the MPI noise depends not only on the optical power, but also on the degree of the frequency chirp of the laser under the direct current modulation [2], [4], [5]. The higher the frequency chirp, the lower is the MPI noise penalty in the transmission system [4], [5]. In the previous experimental studies we found that the frequency chirp parameter, in turn, is proportional to the rate of carrier temperature increase with pumping current [6]–[7]. The coefficient relating the change in carrier temperature and chirp was expressed in terms of the temperature derivative of the optical gain, and two parameters α_T and α_μ. These parameters describe the variation of refractive index produced by the variation of optical gain due to the change of carrier quasi-Fermi level separation and carrier temperature respectively. We measured these parameters for MQW InGaAsP lasers and estimated the rate of the temperature increase with current above threshold [6]–[7].

The presence of carrier heating results in the wavelength chirp that reduces the MPI noise in CATV systems. However the carrier heating can degrade another important characteristic of lasers for such systems, which is the L–I curve linearity. In fact carrier heating was cited as an effect setting a fundamental limit on CATV laser performance [1]. In this paper we use previous experimental results [6]–[9] to estimate various mechanisms through which the carrier heating can cause static nonlinearities. These effects include the dependence of the laser threshold current on temperature, dependence of the heterobarrier leakage and internal quantum efficiency on temperature, and dependence of the internal optical loss and external efficiency on temperature. We then compare estimated values of these nonlinearities to typical values observed in CATV lasers.

The intermodulation distortion (IMD) in CATV lasers is inherently dynamic effect. In order to build an accurate model of this effect it would be necessary to include the time-dependent processes such as electron-photon resonance, transport through the separate confinement layers, and possibly the temporal dynamics of the spatial hole burning along the laser cavity. However it was shown, that rough estimates of IMD may be done on the basis of the static characteristics of the laser, such as L–I curve and radiation spectrum [10]. This static treatment also presents a lower bound for the distortion estimate, because more nonlinear effects are present under modulation than in CW operating regime. The goal of the paper is to demonstrate that the carrier heating gives only a minor contribution to the static nonlinearity, compared to other effects. Therefore it is also not a major contributor to the IMD's in CATV lasers.

II. Phenomenological Treatment

The estimations are performed using simple phenomenological equations describing laser characteristics. The rate equations for carrier and photon density in semiconductor laser are used

$$\begin{aligned}\frac{dn}{dt} &= \frac{I}{eV_{\text{act}}} - \frac{n}{\tau_s} - \frac{c}{N_{\text{eff}}}GS \\ \frac{dS}{dt} &= \frac{c}{N_{\text{eff}}}\Gamma GS - \frac{S}{\tau_p}\end{aligned} \qquad (1)$$

where n and S are carrier and photon concentrations respectively, I is the pumping current, e the electron charge, τ_s the carrier lifetime, c the light velocity in vacuum, N_{eff} the effective refractive index, G the material gain in the active layer, Γ the optical confinement factor, and τ_p the photon lifetime. The inverse photon lifetime is proportional to the total loss α_{tot}. We neglected the spontaneous emission coupling into the lasing mode. The threshold condition results from a

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static treatment of (1)

$$\frac{I_{\mathrm{th}}}{eV_{\mathrm{act}}} = \frac{n_{\mathrm{th}}}{\tau_s}$$
$$\frac{c}{N_{\mathrm{eff}}}\Gamma G = \frac{1}{\tau_p} = \frac{c}{N_{\mathrm{eff}}}\alpha_{\mathrm{tot}}. \tag{2}$$

Here, the photon density is assumed to be zero at threshold. In the static case and at low frequencies (significantly lower than the resonant frequency), the effect of carrier heating on the optical gain cannot cause any static nonlinearities directly, because the value of modal optical gain is pinned to the value of the total optical loss. Any change of the optical gain caused by the carrier heating is compensated for by increasing carrier concentration. Nonlinear effects, however, can arise from the fact that the change in carrier temperature and concentration will lead to a change of total optical loss, recombination rate (described with high accuracy by the threshold current), and heterobarrier leakage. In order to address these effects we use a standard phenomenological formula relating the output power L and pumping current

$$L = \eta_{\mathrm{int}}\frac{\alpha_{\mathrm{mirr}}}{\alpha_{\mathrm{tot}}}(I - I_{\mathrm{th}}) \tag{3}$$

where η_{int} is the internal quantum efficiency, and α_{mirr} the mirror loss. Also a linear relation between the change of carrier temperature and current is used

$$T - T^i = \frac{dT}{dI}(I - I_{\mathrm{th}}) \tag{4}$$

where T^i is the carrier plasma temperature at threshold. The value of dT/dI was determined in [6]–[7] to be approximately 0.13 K/mA. We will analyze the effect of carrier heating on three factors: $\eta_{\mathrm{int}}, \alpha_{\mathrm{tot}}$, and I_{th}, using (4) and the measured dependence of these parameters on current and temperature. The convenient way to quantify the degree of nonlinearity is to estimate the ratio of the second to first derivatives of the output power with respect to current. Finally, they will be compared to a typical measured value of this parameter for CATV lasers.

III. DEPENDENCE OF RECOMBINATION RATE AND THRESHOLD CURRENT ON TEMPERATURE

An increase of temperature results in a reduction of the optical gain and an increase of the total optical loss [8]. The carrier concentration then increases to support lasing action, which causes an increase of the carrier recombination rate. Therefore, threshold current also increases with temperature, which is described by the phenomenological expression

$$I_{\mathrm{th}}(T) = I^i_{\mathrm{th}} \exp\frac{T - T^i}{T_0} \tag{5}$$

where T_0 is the characteristic temperature [11], and I^i_{th} is the threshold current at temperature T^i. Expanding (5) into series up to second order and using (4) yields

$$\begin{aligned} I_{\mathrm{th}}(T) &= I^i_{\mathrm{th}}\left(1 + \frac{T - T^i}{T_0} + \frac{1}{2}\left(\frac{T - T^i}{T_0}\right)^2 + \cdots\right) \\ &= I^i_{\mathrm{th}}\left(1 + \frac{dT}{dI}\frac{I - I^i_{\mathrm{th}}}{T_0} + \frac{1}{2}\left(\frac{dT}{dI}\frac{I - I^i_{\mathrm{th}}}{T_0}\right)^2 + \cdots\right). \end{aligned} \tag{6}$$

Substituting (6) into (3), we obtain

$$\begin{aligned} L = {} & \eta_{\mathrm{int}}\frac{\alpha_{\mathrm{mirr}}}{\alpha_{\mathrm{tot}}}\left(1 - \frac{dT}{dI}\frac{I^i_{\mathrm{th}}}{T_0}\right)(I - I^i_{\mathrm{th}}) \\ & - \frac{1}{2}\eta_{\mathrm{int}}\frac{\alpha_{\mathrm{mirr}}}{\alpha_{\mathrm{tot}}}\left(\frac{dT}{dI}\right)^2\frac{I^i_{\mathrm{th}}}{T_0^2}(I - I^I_{\mathrm{th}})^2 + \cdots. \end{aligned} \tag{7}$$

The increased threshold is accompanied by a reduction of the output efficiency, but for typical values of parameters ($dT/dI = 0.13$ K/mA, $I^i_{\mathrm{th}} = 15$ mA at $T^i = 25$°C, and $T_0 = 60$°C), this reduction is only about 3%. The increased recombination rate results in an increase of the true spontaneous emission (TSE) intensity, which can be recorded from the side of the laser chip [12]. We also observed a similar increase of the TSE intensity for the samples studied in [6]–[7]. This increase is approximately linear in current. The linear increase of the spontaneous emission rate results in some decrease of the first derivative L', but not in a nonzero second derivative L''. Thus, increasing TSE intensity above threshold does not on its own characterize a nonlinearity. The nonlinear effect is characterized by the second term in (7). The nonlinearity parameter in this case is

$$\frac{L''}{L'} = -\left(\frac{dT}{dI}\right)^2\frac{I^i_{\mathrm{th}}}{T_0^2} \approx -0.07\ \mathrm{A}^{-1}. \tag{8}$$

IV. DEPENDENCE OF INTERNAL LOSS ON TEMPERATURE

Another parameter that has a dependence on the temperature which can cause a nonlinearity due to carrier heating is the optical loss. The total loss has to first order a linear dependence on the ambient temperature [8]

$$\begin{aligned} \alpha_{\mathrm{tot}} &= \alpha_{\mathrm{mirr}} + \alpha_{\mathrm{int}} + \frac{\partial\alpha_{\mathrm{int}}}{\partial T}(T - T^i) \\ &= \alpha_{\mathrm{mirr}} + \alpha_{\mathrm{int}} + \frac{\partial\alpha_{\mathrm{int}}}{\partial T}\frac{dT}{dI}(I - I_{\mathrm{th}}). \end{aligned} \tag{9}$$

However, only the fraction of internal loss caused by free-carrier absorption in the active layer is affected by carrier heating. Therefore the linear term in (9) should be multiplied by a factor equal to the ratio of the internal loss in the active layer to the overall internal loss, which was estimated from results of [8]

$$\chi = \frac{\alpha^{\mathrm{active}}_{\mathrm{int}}}{\alpha^{\mathrm{tot}}_{\mathrm{int}}} \approx \frac{1}{4}. \tag{10}$$

We measured the dependence of the internal loss on temperature for the sample used in the previous study [6]–[7], and obtained a value of $\partial\alpha_{\mathrm{tot}}/\partial T \approx 0.08 \pm 0.03\ 1/\mathrm{cm}\cdot\mathrm{K}$. Assuming that the mirror loss is independent of current and temperature, we can estimate the nonlinearity due to the temperature dependence of the internal loss

$$\frac{L''}{L'} = -2\chi\frac{1}{\alpha_{\mathrm{tot}}}\frac{\partial\alpha_{\mathrm{int}}}{\partial T}\frac{dT}{dI} \approx -0.05\ \mathrm{A}^{-1}. \tag{11}$$

V. DEPENDENCE OF THERMIONIC LEAKAGE AND INTERNAL EFFICIENCY ON TEMPERATURE

Thermionic emission of electrons over the heterobarrier into the p-cladding layer is one of the factors determining the internal efficiency of a laser diode [8]. Thermionic leakage increases with the carrier temperature, and therefore the internal efficiency decreases. Again, we consider a linear approximation

$$\eta_{\text{int}} = \eta_{\text{int}}^i + \frac{\partial \eta_{\text{int}}}{\partial T}(T - T^i) = \eta_{i\text{int}}^i + \frac{\partial \eta_{\text{int}}}{\partial T}\frac{dT}{dI}(I - I_{\text{th}}) \quad (12)$$

and use experimental data from [8]. If the doping level in the p-cladding layer at the interface with the separate confinement layer is $5 * 10^{17}$ cm^{-3}, the injection efficiency decreases with increase of temperature at a rate of $\partial\eta_{\text{int}}/\partial T \approx -1.10^{-4}$ K^{-1}. Then similar to (11)

$$\frac{L''}{L'} = -2\frac{1}{\eta_{\text{int}}}\frac{\partial \eta_{\text{int}}}{\partial T}\frac{dT}{dI} \approx -0.03 \text{ A}^{-1}. \quad (13)$$

VI. CONCLUSIONS

We have considered three mechanisms through which the carrier heating can affect the linearity of a semiconductor laser. Using the experimentally determined rate of carrier heating and other experimental data, we estimated the values of possible nonlinearities. Composite nonlinearity produced by the analyzed effects is about 0.15 A^{-1}. This value is order of magnitude smaller than values observed experimentally. This indicates that effects other than carrier heating cause the static nonlinearity in semiconductor lasers. Even more effects will add to nonlinearity of L–I relation under frequency modulation, and the IMD is usually larger than can be estimated from the static L–I curve. At the same time the effect of carrier heating on IMD is frequency independent in the CATV range (below 1GHz) because the carrier heating is characterized by the very fast time constants of order of picosecond or less [1]. Therefore, we conclude that the carrier heating does not contribute significantly not only to the static nonlinearities, but also to the IMD of CATV lasers.

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