Modulation response of Quantum Well lasers with carrier transport effects under weak optical feedback

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Abstract

We theoretically investigate the influence of optical feedback on the modulation response of quantum-well lasers. Controlled weak optical feedback is shown to be useful in overcoming the high frequency limitations imposed by carrier-transport effects. With a fine tuning of the external cavity length the maximum attainable modulation bandwidth can be increased.

Modulation bandwidths (f_{3dB}) higher than in bulk devices have been recently demonstrated in Quantum-Well (QW) lasers, achieving 40 GHz [1] and 25 GHz [2] for InGaAs/GaAs and InGaAsP/InP material systems, respectively. However, while the maximum intrinsic modulation bandwidth f_{3dB}^{max} is limited in bulk lasers by damping, carrier transport introduces additional limitations in QW lasers [3, 4]. For bulk lasers f_{3dB}^{max} is expressed in terms of the K-factor as $f_{3dB}^{max} \approx 8.9/K$ [5], with $K = 4\pi^2(\tau_p + \frac{\epsilon}{\nu_g g_n})$ (see Table I for parameter definitions). Carrier transport in QW lasers, including carrier diffusion across the confinement layer, carrier capture into the QW (both processes characterized by a single effective capture time τ_{cap}), and carrier escape out of the QW (with effective escape time τ_{esc}) influences the small signal modulation response (MR) in two ways: *i)* it introduces a parasitic-like low frequency roll-off, with cut-off frequency $(2\pi\tau_{cap})^{-1}$ and *ii)* it decreases the effective differential gain and increases the apparent K-factor when the ratio τ_{cap}/τ_{esc} is comparable to or higher than one. The consequence is that f_{3dB}^{max} in QW lasers, due to transport effects, can be reduced in comparison with the attainable values for laser structures where these effects do not come into play.

The performance of a laser diode can be greatly modified by optical feedback [6],[7]. In particular, the MR of bulk lasers is known to be significantly affected by optical feedback [8]. It is also known that small amounts of feedback are useful for linewidth reduction, but large feedback intensities can degrade the laser performance through the occurrence of the "coherence collapse" which gives rise to several GHz linewidth [6],[7]. Pattern effects and jitter of large-signal intensity modulated lasers are also drastically changed by weak optical feedback in extremely short external cavities as has been shown analitically and numerically [9], and experimentally [10].

In this work we explore the effects of weak optical feedback from short external cavities of length $L_E \approx 1.5$ mm (which correspond to an external round-trip time $\tau_E \simeq 10$ ps) in the small signal modulation properties of QW lasers, and we find that it can be instrumental in modifying and compensating the detrimental carrier transport effects.

Our analysis is based on standard single-mode rate equations for QW lasers [3], which incorporate the dynamics of the unconfined carriers in the confinement and barrier regions (core). These equations are supplemented by weak feedback terms describing single reflection for an external reflector in the way described by Lang and Kobayashi for bulk lasers [8]. Optical feedback is characterized by τ_E and the coupling parameter $\kappa = \frac{\sqrt{R_{ext}}(1-r)}{\tau_L\sqrt{r}}$, with R_{ext} the power external reflectivity, r the laser-facet reflectivity and τ_L the laser cavity round-trip time. The equations for the photon number S in the cavity, the optical phase ϕ, the carrier number in the QWs N_ω, and the carrier number in the core N_b are:

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\begin{aligned}
\frac{dS(t)}{dt} &= \left(\frac{\Gamma\nu_g g_n(N_\omega - N_t)}{V_{QW}(1+\epsilon S(t))} - \frac{1}{\tau_p}\right) S(t) + \frac{\beta}{\tau_{eff}} N_\omega \\
&+ 2\,\kappa\sqrt{S(t-\tau_E)S(t)}\cos\left[\omega_s\tau_E + \phi(t) - \phi(t-\tau_E)\right] && (1)\\
\frac{d\phi(t)}{dt} &= \omega_t - \omega_m + \frac{\alpha}{2}\frac{\Gamma\nu_g g_n(N_\omega - N_t)}{V_{QW}(1+\epsilon S(t))} \\
&- \kappa\sqrt{\frac{S(t-\tau_E)}{S(t)}}\sin\left[\omega_s\tau_E + \phi(t) - \phi(t-\tau_E)\right] && (2)\\
\frac{dN_\omega}{dt} &= \frac{N_b}{\tau_{cap}} - \frac{N_w}{\tau_{esc}} - \frac{N_w}{\tau_{eff}} - \frac{\Gamma\nu_g g_n(N_\omega - N_t)}{V_{QW}(1+\epsilon S(t))} S(t) && (3)\\
\frac{dN_b}{dt} &= \frac{I}{e} - \frac{N_b}{\tau_{cap}} + \frac{N_\omega}{\tau_{esc}} \quad , && (4)
\end{aligned}
$$

where I denotes the bias current, e the electronic charge, ω_s and ω_m the stationary optical frequencies with and without feedback, respectively, and ω_t the frequency at transparency. Other parameters are defined in table I. We find the stationary solution of (1)-(4) which describes the feedback- modified laser emission, and calculate the MR by a small-signal analysis in the vicinity of such solution.

We illustrate the effects of feedback on the MR using the experimentally determined parameters for a p-doped InGaAs/GaAs QW laser [10], given in table I. These lasers have demonstrated 30 GHz modulation bandwidth and the K-factor yields $f_{3dB}^{max} = 63$ GHz. Transport effects are not important for this laser structure ($\tau_{cap} \approx 2$ ps and $\tau_{esc} > 1$ ns [12]), but we study the feedback influence by assuming different τ_{cap} and τ_{esc}. In the calculations we consider a fixed $\kappa = 0.05$ ps^{-1}, which correspond to $R_{ext} \approx 0.05$, and use τ_E as the parameter controlling feedback. Monitoring τ_E fixes the phase of the reinjected field. The variations in threshold current ($I_{th} \simeq 17.6$ mA) and emission wavelength ($\lambda = 1.095$ μm) due to feedback are $< 10\%$ and $<< 1\%$, respectively.

Figure 1 shows typical modifications of the MR due to optical feedback. We plot the MR at $I = 3.5 I_{th}$ for the solitary laser ($\kappa = 0$, curve e) and the laser with feedback (curves a-d). It is clear that both, the apparent resonance frequency and the damping, are extremely sensitive to τ_E. By an appropriate choice of τ_E, it is possible to increase f_{3dB} up to $20 - 30\%$ with respect to the solitary laser. The dependence of f_{3dB} on τ_E is shown in figure 2, considering the cases $\tau_{cap} << \tau_{esc}$, $\tau_{cap} \sim \tau_{esc}$ and $\tau_{cap} \to 0$, $\tau_{esc} \to \infty$, the latter being the limit for a bulk laser. The modulation bandwidth oscillates periodically with the external round-trip time τ_E with a period of 0.005 ps. Consequently, the high-frequency performance can be improved if τ_E is carefully adjusted with a precision $<< \Delta\tau_E$, i.e. L_E should be controlled within half optical wavelength. Such fine control can be achieved either by using an external reflector controlled with high-precision positioners, or by integrating the laser diode together with a reflector and controlling the optical length, similarly to the phase control in multisection lasers. Our results show that the optimum τ_E presents a weak dependence on the injection level and therefore a close-loop system could look automatically for the best feedback conditions.

The physics behind the feedback effects on the MB is related to the coupling between the intensity and the frequency modulation, as it has been discussed by Peterman [6] and therefore it is aplicable to both bulk and quantum well lasers. Simulations on the feedback influence on a bulk laser ($\tau_{cap} \to 0$, $\tau_{esc} \to \infty$ and standard bulk laser parameters [13]) yield variations of the MR qualitatively similar to those shown in figs. 1 and 2.

We emphasize the possible improvements in QW lasers due to their high speed potentialities and to their intrinsic limitations caused by transport effects. On the other hand, figures 1 and 2 show that a weak unintentional feedback level can reduce drastically the high-frequency performance without apparently affecting other device characteristics such as emission wavelength or threshold current and this should be taken into account when operating the laser in real conditions or when measuring its characteristics.

Figure 3 illustrates the possible improvements on f_{3dB} for the QW laser whose parameters are shown in table I and with different regimes of τ_{cap} and τ_{esc}. We plot the dependence of f_{3dB} on the injection current considering the optimum feedback $\tau_{esc} = 10.003\,ps$ and different regimes of τ_{esc} and τ_{cap}. In fig. 3a) we consider $\tau_{cap} = 2$ ps, i.e., the cut-off frequency due to τ_{cap} is much higher than the K-factor limit. For $\tau_{esc} = 2$ ns, f_{3dB}^{max} for the solitary laser is $\simeq$ 56 GHz (curve A), corresponding to $\approx 8.9/K$, while the response with optimized feedback can achieve up to $\simeq$ 65 GHz (curve B). On the other hand, for $\tau_{esc} = 2$ ps, f_{3dB}^{max} for the solitary laser is reduced due to the high value of τ_{cap}/τ_{esc} down to 30 GHz (curve C). The use of optimized feedback improves f_{3dB}^{max} up to $\simeq 50$ GHz (curve D) almost reaching the value for the laser with negligible transport effects. In fig. 3b) we consider the case of lasers with $\tau_{cap} = 5$ ps in which f_{3dB}^{max} is limited by τ_{cap}. For the solitary laser with $\tau_{esc} = 2$ ns, f_{3dB} has a maximum of $\simeq 35$ GHz but saturates to $(2\pi\tau_{cap})^{-1} \simeq 30$ GHz (curve A). By using an optimum feedback, f_{3dB} is enhanced up to $\simeq 55$ GHz (curve B). The improvement is more significant at a certain current range. Finally, both detrimental transport effects are considered for the solitary laser in curve C ($\tau_{esc} = \tau_{cap}$). The response is again improved by controlled feedback (curve D). However, for large input currents f_{3dB} saturates very fast to the value without feedback.

In summary, controlled weak optical feedback gives the possibility of overcoming the limitations in the maximum intrinsic modulation frequency imposed by carrier transport effects in QW lasers. In cases in which τ_{cap} alone does not limit f_{3dB}^{max} but $\tau_{cap} \simeq \tau_{esc}$, it is possible to choose the external cavity length in such a way that optical feedback improves the f_{3dB} to those of situations in which carrier transport effects can be neglected. Moreover, if in this situation the external mirror is carefully adjusted the relaxation oscillation frequency could be very small with a still large f_{3dB}. In cases in which f_{3dB}^{max} is limited by τ_{cap} there is an optimum range of injection currents for which the maximum attainable frequency can be increased by weak optical feedback.

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Table I

Meaning and values of the different parameters appearing in the model

Parameter	Meaning	Value	Units
Γ	Optical confinement factor	0.088	adim.
V_{QW}	Volume of Quantum Wells	2.05×10^{-11}	cm^3
ν_g	Group velocity	7.7×10^9	cm/s
g_n	Differential gain	2.5×10^{-15}	cm^2
N_t	Carrier number at transparency	8.2×10^6	adim.
ϵ	Nonlinear gain saturation	2×10^{-7}	adim.
β	Spontaneous emission factor	$1{\times}10^{-5}$	adim.
α	Linewidth enhancement factor	1.4	adim.
τ_p	Photon lifetime	1.2	ps
τ_{eff}	Carrier lifetime in the QWs	0.17	ns

Figure Captions

Figure 1. Modulation response (f_{3db}) vs. modulation frequency for $\kappa = 0.05$ ps^{-1} and different τ_E (A-D) and $\kappa = 0$ (E), with $\tau_{cap} = 2$ ps and $\tau_{esc} = 2$ ns.

Figure 2. Modulation response (f_{3db}) vs. the external round-trip time τ_E, for $\tau_E \sim 10$ ps, $\kappa = 0.05$ ps^{-1} and injection current 3.5 I_{th}. Solid line corresponds to a bulk laser, dashed line corresponds to a QW laser with $\tau_{cap} = 5$ ps and $\tau_{esc} = 2$ ns and three-dot-dash line corresponds to a QW laser with $\tau_{cap} = \tau_{esc} = 5$ ps. The horizontal lines correspond to the value of the f_{3db} without feedback.

Figure 3. Modulation bandwidth vs. $(I - I_{th})^{1/2}$ for $\tau_{cap} = 2$ (panel a) and 5 ps (panel b). Solid lines $\kappa = 0$ (A: $\tau_{esc} = 2$ ns, and C: $\tau_{esc} = \tau_{cap}$); dashed lines $\kappa = 0.05$ ps^{-1} and $\tau_E = 10.003$ ps (B: $\tau_{esc} = 2$ ns, and D: $\tau_{esc} = \tau_{cap}$).