

# Analysis of Pump Probe Measurements and Carrier Overflow Effects in Multiple Quantum-Well Optical Amplifiers

Nir Tessler, A. Berenzon, and Gadi Eisenstein

**Abstract**— We present a theoretical study of structure dependent effects on carrier dynamics in simulated pump probe experiments of quantum-well optical amplifiers. We find that the dynamics of the unconfined carriers alter the probe transmission. We show that local capture has an effect which is similar to that of carrier cooling, and that by taking into account the carrier induced waveguide loss in a dynamic fashion, we can explain a previously measured transmission overshoot.

THE characteristics of diode lasers and optical amplifiers are determined by the details of carrier dynamics. Direct experimental determination of carrier dynamics is, by nature, not possible. Therefore, indirect studies, based on measurements of gain dynamics [1], [2] spontaneous emission [3], [4] or modulation responses [5] have to be used and related to the actual carrier dynamics through modeling. The interpretation of such indirect experiments in terms of carrier dynamics is difficult since it requires an exact description of the physical processes governing a particular experiment.

This paper addresses this difficulty in the context of experiments which use changes in transmission of an optical probe, following an optical excitation, to map out gain evolution. The most widely used technique of this kind, and the one which will be simulated here, is the short pulse pump probe technique. The origin of the difficulty lies in the fact that the injected photons overlap the entire optical waveguide of the laser and hence sense the response of a multimaterial structure and not only of the actual gain region. This issue becomes of prominent significance in quantum-well (QW) amplifiers [6] where the gain takes place in a small part of the waveguide volume. In the following, we present calculations of carrier and optical probe transmission responses in simulated pump probe experiments on QW optical amplifiers. We identify various effects which determine the probe transmission and shed light on an ambiguous experimental observation related to a transmission overshoot in pump probe measurements of such QW optical amplifiers [7].

Carrier dynamics are modeled here using the detailed carrier injection model described in [8] and [9]. Briefly, that model describes the carrier injection process in terms of transport of carriers (separately holes and electrons) which are injected

from their respective contacts into the three-dimensional (3-D) optical waveguide and a transfer of carriers into the two-dimensional (2-D) wells (where the gain takes place) which is described by a local capture rate [8], [9]. The continuity equation for the carrier density  $N$  is

$$\dot{N}_B = \nabla \cdot [D \nabla N_B + \mu N_B E] - R_B - R_C. \quad (1)$$

In (1), subscript  $B$  represents 3-D carriers,  $N_B$  and the electric field  $E$  are functions of space and time, the mobility  $\mu$  is a function of  $E$ , and the diffusion coefficient is  $D$ . The term  $R_B$  represents conventional recombination and  $R_C$  is the carrier capture rate which may be carrier density dependent [9]. A second continuity equation describing the rate of change of the 3-D holes ( $P_B$ ) has the same form as (1) with  $D$ ,  $\mu$ , and  $R_C$  taking the values appropriate for holes.

The 2-D carrier-photon interactions are described by two rate equations for electrons and holes as well as a photon rate equation.

$$\dot{N}_{Qj} = R_{Cj} - R_{Qj} - G_j S \quad (2)$$

In (2), subscript  $Q$  now represents 2-D carriers so that  $N_{Qj}$  is the electron density in the  $j$ 's well. The term  $R_{Cj}$  is the capture rate into the  $j$ 's well,  $R_{Qj}$  represents recombination,  $G_j$  is the gain, and  $S$  the photon density. A similar equation is used for the 2-D holes  $P_Q$ . For the photons the rate equation is

$$\dot{S} = \sum_j \Gamma_j \{G_j S + \gamma B N_{Qj} P_{Qj}\} - S/\tau_p \quad (3)$$

where  $\gamma$  represents the fraction of spontaneous emission coupled into the lasing mode and  $B$  is the bimolecular recombination coefficient.

The electron-hole Coulomb interaction is included via the Poisson equation which is solved self consistently.

$$\nabla \cdot E = \frac{q}{\epsilon} [P - N] \quad (4)$$

$P$  and  $N$  in (4) are total carrier densities (the sum of 3-D and 2-D).

The present calculations use that model to evaluate time resolved carrier distributions from which the various gain and waveguide parameters are determined. The transmission of the optical probe is calculated by solving the scalar wave equation for the TE polarization.

$$\nabla^2 E_t = (\beta^2 - n^2 k^2) E_t \quad (5)$$

Manuscript received May 6, 1994.  
The authors are with the Advanced Optoelectronics Center, Department of Electrical Engineering, Technion, Haifa 32000, Israel.  
IEEE Log Number 9405201.

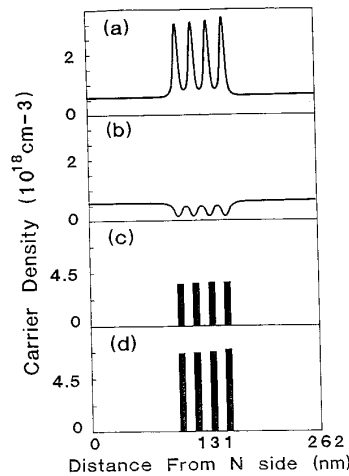


Fig. 1. Steady state carrier distributions. (a) 3-D electrons. (b) 3-D holes. (c) 2-D electrons. (d) 2-D holes.

In (5),  $n$  is the position dependent complex index of refraction and  $E_t$  is the transverse field distribution. The solution of (5) takes into account the following: a) the gain in the wells [11]; b) the losses due to intervalence band absorption (IVBA) in the QW [11] and in the optical waveguide [12]; c) the carrier induced index change [13] that is smaller for 3-D carriers compared to 2-D carriers. When solving the wave equation we do not consider the finite probe width in the time or frequency domains. The calculations neglects distributed effects resulting from the fact that the optical pulses are shorter than the transit time in the amplifier. We believe that this approximation does not affect the results presented here.

The present calculations are specifically aimed at describing carrier overflow effects. Hence, the other important nonlinearities; carrier heating and cooling, spectral hole burning, and two photon absorption *are not included in a dynamic fashion* [2]. The nonlinearity of the gain is modeled only by the usual nonlinear gain coefficient  $\epsilon$  [5]. The structure that we study is a separate confinement heterostructure (SCH) QW laser amplifier. It consists of four 8-nm wide InGaAs wells separated by 10 nm wide InGaAsP barriers and a 100 nm optical confinement layer. The barrier bandgap is chosen to be  $1.36 \mu\text{m}$  to ensure that carrier overflow effects are pronounced.

To set up the dynamic solutions we calculate first, for a given bias level, the steady state hole and electron distributions in the various wells and along the optical waveguide. Figs. 1(a) and (b) describe the 3-D electron and hole distributions along the growth axis, respectively. Figs. 1(c) and 1(d) describe the 2-D electron and hole distributions among the four wells. We note two important points: a) there is a non-negligible population of all 3-D waveguide states; b) in the QW region, the density of the 3-D holes is very small compared to the 3-D electrons. These features result from the relevant densities of states and the effective mass of holes which is much larger than that of the electrons [9]. The importance of the 3-D carriers is enhanced due to their large optical confinement factor ( $\approx 40\%$ ) compared to that of the 2-D quantum wells ( $\approx 6\%$ ).

In the first dynamic calculation we present, we follow the response of the carrier distributions to a 200 fs Gaussian shaped optical pump pulse with an energy of 0.3 pJ. The center of the pulse is defined as  $t = 0$ . The bias was set to 40 mA assuming a  $650 \mu\text{m}$  long device with a  $2 \mu\text{m}$  wide waveguide. In the following graphs the wells are numbered from 1 to 4 with well number 1 being the closest to the  $N$  contact. Fig. 2(a) shows, for each well separately, that the 2-D electron density drops at  $t = 0$ , and then recovers with two time constants. The fast time constant is on the order of 1 ps and is due to capture of high energy electrons located at the well region, namely the usual local capture [8]. The longer time constant is of a few ps and is an average diffusion time across the optical confinement layer to the QW. As for the 2-D holes [Fig. 2(b)], the response is similar but the fast time constant in the recovery is absent. The local hole capture is not observable since the 3-D hole population is very small in the well region. In other words, most of the holes are always captured, see Fig. 1. Since the dynamic excitation in the present case is optical, the diffusion process observed in Fig. 2 can be described reasonably well as an ambipolar diffusion [7]. Fig. 3 shows calculated transmission of a probe pulse assuming a  $650 \mu\text{m}$  uniform amplifier. It is obvious that the fast local capture is also observable in the calculated response of the probe transmission which resembles previously published measured data [7], [14]. Also, the calculation yields a transport time constant of 7.5 ps which is close to the measured value of 7 ps stated in [7]. Two issues are highlighted by this result. First, measured probe transmission dynamics cannot separate the responses of the different wells, let alone the differences between hole and electron dynamics. Second, this result suggests that the fast time constant measured in QW amplifiers results *not only* from cooling of 2-D carriers as stated in [7], [14] but is also due to the relaxation (capture) of 3-D carriers into the wells. Since these two time constants are of similar magnitudes ( $\approx 1$  ps), they constitute some single effective time constant. Also, it was recently shown that the capture time is concentration dependent [10]; this suggests that measured recovery times may depend on the bias current.

The simulated pump pulse energy we used in the above calculations is in the sub-pJ range. This ensures that the simulation is in the small signal regime where the response is linear. The linearity is important since it enables the separation of different mechanisms according to their characteristic time constants. We have repeated the simulation for high energy pump pulses and found that while using fitting procedure routinely used in the linear regime [14], we obtain a significant enhancement of the time constants (an approximately 20% increase for 10 pJ pump pulses). This results points to the absolute need to use low energy pump pulses in gain dynamic experiments where the interpretation of the results assume linearity of the response.

The last calculation we present simulates the pump probe experiment in a QW amplifier presented in [7]. That experiment used a 7 ps wide pulse and yielded an unusual overshoot in the probe transmission. Using the model described here, we have simulated that experiment using the stated device parameters and operating conditions [7]. The

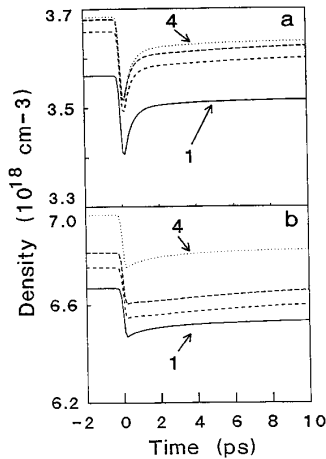


Fig. 2. Response to a 200 fs, 0.3 pJ pulse. (a) Response of 2-D electrons in each well. (b) Response of 2-D holes in each well.

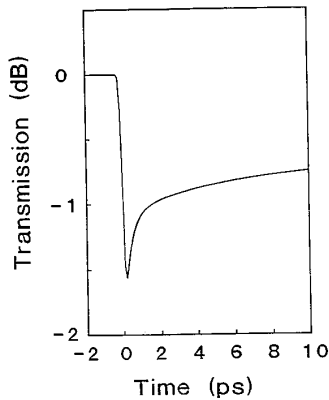


Fig. 3. Response of a calculated probe transmission to a 200 fs, 0.3 pJ pump pulse.

simulation is aimed at explaining the fundamental processes involved in the observed dynamics and is not meant to fit minor details of a specific measurement. Fig. 4 shows the calculated transmission dynamics for different probe wavelengths. In this calculation, the amplifier was again assumed to be  $650\ \mu\text{m}$  long and the current was chosen to be 300 mA. The important parameters of the simulation as gain, loss, and index of refraction were not fitted to the published experimental results. Rather, known carrier dependent values [11], [13] were used yielding the calculated results shown in Fig. 4. These calculated results of the transmission overshoot and its dependence on wavelength are in good agreement with the measured data in [7]. Two possible mechanisms may explain the transmission overshoot: a) an increase in the confinement factor caused by carrier induced refractive index changes, as proposed in [7]; b) reduction of the carrier induced waveguide loss (mainly inter valence band absorption, IVBA). In Fig. 5 we separate these two effects for two wavelengths,  $1.55\ \mu\text{m}$  and  $1.50\ \mu\text{m}$ . The bottom curve in each case describes the change in the transmission due to

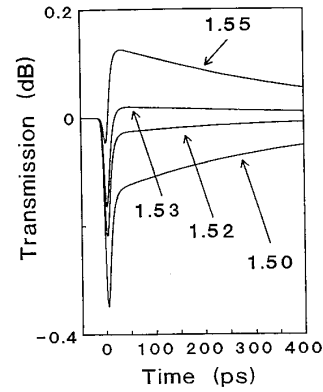


Fig. 4. Response of a calculated probe transmission at several wavelengths to a 7 ps pump pulse.

changes in the QW gain  $g(t)$  only, meaning all changes in loss  $\alpha(t)$  or in the optical confinement  $\Gamma$  are not included so the transmission evolution is described by  $g(t)\Gamma_{QW}(0)(\Gamma_{QW}$  is the optical confinement factor of the quantum wells). The next curve adds the effect of changes in the carrier (and hence time) dependent confinement factor so the transmission behaves like  $g(t)\Gamma_{QW}(t)$ . The third curve is calculated for a constant confinement factor but accounts for the change in waveguide loss so the transmission is  $g(t)\Gamma_{QW}(0) - \alpha(t)\Gamma_{WG}(0)(\Gamma_{WG}$  is the optical confinement factor of the waveguide). The upper curve shows the combined effects  $g(t)\Gamma_{QW}(t) - \alpha(t)\Gamma_{WG}(t)$ , with the transmission at  $1.55\ \mu\text{m}$  [Fig. 5(a)] showing an overshoot while the transmission at  $1.50\ \mu\text{m}$  [Fig. 5(b)] does not. It is clear that the time dependence of both the optical confinement and the waveguide absorption loss contribute. However, the absorption changes dominate. In order not to over estimate the overflow effect at high currents one must consider the following: a) the carrier distribution between quantum wells and barriers regions is set by the electron hole interaction [8], [9] and is *not* a simple volume ratio, b) the 3-D carriers are at high energy and have a relatively small effect on the refractive index at the probe wavelength [12].

A comparison between the bottom curves of Fig. 5(a) and 5(b) yields that the reason that overshoot is not observed at  $1.50\ \mu\text{m}$ , is the larger gain reduction (at  $t = 0$ ) at this wavelength. This suggests that for a transmission overshoot to occur two conditions must be met: a) a high population of the 3-D waveguide states is required; b) the differential gain (with respect to carrier density) should be saturated. These two conditions are easily achieved in structures with low barrier height driven at large bias levels and probed at the long wavelength side of the gain spectrum. These were indeed satisfied in the experiments reported in [7].

To conclude, we have presented a theoretical calculation relating carrier and gain dynamics in QW optical amplifiers and pointed out some of the difficulties associated with interpreting pump-probe data in QW based structures. We further showed that the unconfined carriers have a major effect on the measured probe transmission. On a short time scale, the local capture and the carrier cooling processes are inseparable

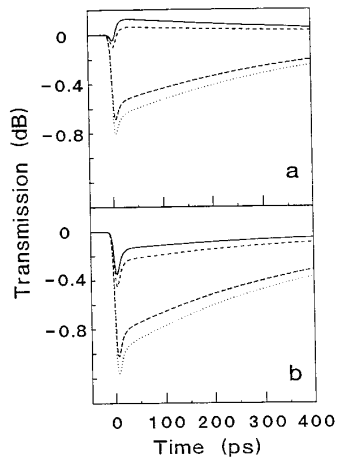


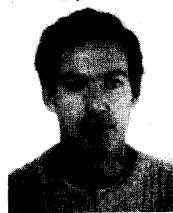
Fig. 5. Response of a calculated probe transmission to a 7 ps pulse separated into different effects. (a) Wavelength = 1.55  $\mu\text{m}$ . (b) Wavelength = 1.50  $\mu\text{m}$ .

and both contribute to measured time constant on the 1-ps time scale. We also find that in cases where the 3-D states are populated, they affect the lasing mode through the modification of the waveguide loss. On time scales of approximately 50 ps, this effect manifest itself, sometimes, as transmission overshoot. Our results shows that these losses reduce significantly the differential gain. This contributes to the large linewidth enhancement factor measured in QW amplifiers [15]. As for the pump intensity, we have pointed out the significance of using low pump intensities since the use of pulses with energies larger than few pJ alters the measured response to the point where physical processes can no longer be separated according to their characteristic time constants and hence, the interpretation of results becomes very difficult. Finally, we address the issue of modeling QW lasers and optical amplifiers. Our results shows that a QW laser model *must* include the local capture time. In many cases there are modifications to the optical confinement region and than one should consider the dynamics of the waveguide loss as well as the refractive index changes. It turns out however, that the former plays a more significant role.

#### REFERENCES

- [1] M. P. Kessler and E. P. Ippen, "Subpicosecond spectral gain dynamics in AlGaAs laser diodes," *Electron. Lett.*, vol. 24, no. 17, pp. 1102-1103, 1988.
- [2] J. Mark and J. Mork, "Subpicosecond gain dynamics in InGaAsP optical amplifiers: Experiment and theory," *Appl. Phys. Lett.*, vol. 61, no. 19, pp. 2281-2283, 1992.
- [3] B. Deveaud, J. Shah, T. C. Damen, and W. T. Tsang, "Capture of electrons and holes in quantum wells," *Appl. Phys. Lett.*, vol. 52, pp. 1886-1888, 1988.
- [4] R. Nagar, N. Tessler, D. Abraham, G. Eisenstein, U. Koren, and G. Raybon, "Measurements of the barrier-well injection bottleneck in a multiple quantum well optical amplifier," *Appl. Phys. Lett.*, vol. 60, no. 15, pp. 1788-1790, 1992.

- [5] I. P. Kaminow and R. S. Tucker, "Mode controlled semiconductor lasers," in *Guided-Wave Optoelectronics*, T. Tamir, Ed. Berlin, Germany: Springer-Verlag, 1988.
- [6] G. Eisenstein, U. Koren, G. Raybon, T. L. Koch, J. M. Wiesenfeld, M. Wegener, R. S. Tucker, and B. I. Miller, "Large and small signal gain characteristics of 1.5  $\mu\text{m}$  multiple quantum well optical amplifiers," *Appl. Phys. Lett.*, vol. 56, no. 13, pp. 1201-1203, 1990.
- [7] G. Eisenstein, J. M. Wiesenfeld, M. Wegener, G. Sucha, D. S. Chemla, S. Weiss, G. Raybon, and U. Koren, "Ultra fast gain dynamics in 1.5  $\mu\text{m}$  multiple quantum well optical amplifiers," *Appl. Phys. Lett.*, vol. 58, no. 14, pp. 158-160, 1991.
- [8] N. Tessler, R. Nagar, D. Abraham, G. Eisenstein, U. Koren, and G. Raybon, "Coupling between barrier and quantum well energy states in a multiple quantum well optical amplifier," *Appl. Phys. Lett.*, vol. 60, no. 6, pp. 665-667, 1992.
- [9] N. Tessler and G. Eisenstein, "On carrier injection and gain dynamics in quantum well lasers," *IEEE J. Quantum Electron.*, vol. 29, pp. 1586-1595, 1993.
- [10] P. W. Blom, J. E. M. Haverkort, P. J. van Hall, and J. H. Wolter, "Carrier-carrier scattering induced capture in quantum well lasers," *Appl. Phys. Lett.*, vol. 62, pp. 1490-1492, 1993.
- [11] M. Asada, A. Kameyama, and Y. Suematsu, "Gain and intervalence band absorption in quantum well lasers," *IEEE J. Quantum Electron.*, vol. 20, pp. 745-753, 1984.
- [12] H. C. Casey, Jr. and P. L. Carter, "Variation of intervalence band absorption with hole concentration in P-type InP," *Appl. Phys. Lett.*, vol. 44, pp. 82-83, 1984.
- [13] S. Shin and C. B. Su, "The sublinear relationship between index change and carrier density in 1.5 and 1.3  $\mu\text{m}$  semiconductor lasers," *IEEE Photon. Technol. Lett.*, vol. 4, pp. 534-537, 1992.
- [14] K. L. Hall, G. Lenz, E. P. Ippen, U. Koren, and G. Raybon, "Carrier heating and spectral hole burning in strained-layer quantum-well laser amplifiers at 1.5  $\mu\text{m}$ ," *Appl. Phys. Lett.*, vol. 61, pp. 2512-2514, 1992.
- [15] N. Storkfelt, M. Yamaguchi, B. Mikkelsen, and K. E. Subkjaer, "Recombination constants and  $\alpha$  factors in 1.5  $\mu\text{m}$  MQW optical amplifiers taking carrier overflow into account," *Electron. Lett.*, vol. 28, pp. 1774-1776, 1992.



Nir Tessler received the B.Sc. and M.Sc. degrees in electrical engineering from Technion—Israel Institute of Technology, Haifa, Israel, in 1990 and 1992, respectively.

He is currently a Ph.D. candidate in the Electrical Engineering Department at the Technion. His current interests are in the dynamics of fast optoelectronic devices.

A. Berenzon, photograph and biography not available at the time of publication.

Gadi Eisenstein received the B.Sc. degree from the University of Santa Clara, Santa Clara, CA, in 1975; and the M.Sc. and Ph.D. degrees from the University of Minnesota, Minneapolis, in 1978 and 1980, respectively.

In 1980, he joined AT&T Bell Laboratories where he was a member of the Technical Staff in the Photonic Circuits Research Department. His research at AT&T Bell Laboratories was in the field of high-speed optoelectronic devices optical amplification, optical communication systems, and thin film technology. In 1989, he joined the faculty of the Technion—Israel Institute of Technology, where he is a Professor of Electrical Engineering and a member of the Technion Advanced Optoelectronics Center.