Light Dependence of a Semiconductor Optical Amplifier's Recovery Rate

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Semiconductor Optical Amplifier (SOA) recovery times are investigated by simultaneously pumping a CW optical beam and an optical pulse through a SOA. An analytic expression that predicts the effective recovery time in the presence of a CW optical beam is derived from a SOA model. The predicted recovery time is verified via simulations and experiments. It was found that an increase in CW beam power caused a decrease in recovery time. The SOA's carrier number varies along the length as a function of the injected light and this is incorporated into the model used in the simulations to achieve estimations of the recovery time and carrier number.

I. Introduction

The recovery time of a SOA becomes important at very high bit rates. In order to reduce the SOA's recovery time a saturating optical signal is injected into the SOA. When two short pulses enter the SOA in quick succession the first pulse would recombine some of the free carriers (depending on it's intensity), thus reducing the number of free carriers that will be available to the second pulse. If the second pulse follows the first pulse in a short enough time the biasing current alone will not be able to replenish sufficient free carriers in due time for the second pulse. Thus the optical holding beam's photons increases the amount of free carriers that will be available before the second pulse enters. Because of the process of stimulated emission some of the holding beam's photons will also cause a decrease in the total amount of free carriers available to both pulses. This means a decrease in gain for the pulses entering the SOA. Thus a trade-off is made between a loss of gain and an increase in recovery time.

We will refer to the new carrier lifetime in the presence of a cw holding beam as the effective carrier lifetime (τ_{eff}). Manning and Davies have derived an analytic equation for the effective carrier lifetime in the presence of an optical holding beam by looking at the SOA as a single point in space [1]. We propose a different analytic equation that takes into account that the SOA's carrier number varies along the length as a function of the injected light and this is incorporated into the model used in the simulations to achieve estimations of the recovery time and carrier number. The value of the recovery time is important because it helps in optimizing the speed of the optical signal processing function. In section II of this paper the theory behind the analytic equation is discussed, then in section III the numerical results are compared with the new analytic equation's results and the Manning and Davies analytic equation's results. In the conclusion we discuss the results.

II. Theory

The analytic equation for the effective recovery time that Manning and Davies give looks as follows [1]:

$$\tau_{eff} = \frac{\tau_e \tau_h}{(\tau_e + \tau_h)}. \qquad (1)$$

In (1) τ_{eff} is the effective carrier lifetime in the presence of an optical holding beam, τ_e is the carrier lifetime in the absence of an optical holding beam, and τ_h is a holding beam dependent term at high powers that is defined as

$$\tau_h = \frac{E^{sat}}{P_h}. \qquad (2)$$

In (2) P_h is the power of the cw holding beam (the saturating optical signal) and the saturation energy E^{sat} is defined as E^{sat} = $(A\ \ \omega_h)/(\Gamma a)$, where A is the area of the active region, $\ \omega_h$ is the photon energy of the holding beam's photons, Γ is the mode confinement factor and a is the gain coefficient.

We propose a different analytical equation that takes into account that the carrier number varies along the length of SOA as a function of the injected light. We start with the following form of the rate equation:

$$\frac{\partial N(z)}{\partial t} = \frac{I}{q} - \frac{N(z)}{\tau_e} - \Gamma G \left[\frac{e^{(\Gamma G - \alpha_{\text{int}})z} - 1}{2z(\Gamma G - \alpha_{\text{int}})} \right] P_{in}. \qquad (3)$$

In (3) N is the carrier number, I is the SOA bias current, q is the electronic charge, v_g is the group velocity, z is the distance along the length of the active region, α_{int} is the internal losses, P_{in} is the optical power input to the SOA. In (3) it can be seen that the change in carrier density is dependent on the length of the SOA. The third term on the right hand side of (3) is obtained by solving the rate equation for the carrier photon number. G is the small signal gain and is defined as

$$G(N) = \frac{a}{V}(N - N_0). \qquad (4)$$

In (4) V is the volume of the active region and N_0 is the carrier number at transparency. We substitute the third term on the right hand side of (3) with a second order Taylor series expansion around a steady state value of the carrier number (N_s). If we substitute this term into (3) and ignore terms containing carrier numbers to the second order or higher orders (because we are only interested in the recovery time) (3) will look as follows:

$$\frac{\partial N}{\partial t} = \frac{I}{q} - \Gamma G(N_s) P_{in} \left[\frac{e^{(\Gamma G(N_s) - \alpha_{\text{int}})z} - 1}{2z(\Gamma G(N_s) - \alpha_{\text{int}})} \right] + A_c P_{in} N_s - \left[\frac{1}{\tau_e} + v_g A_c P_{in} \right] N \qquad (5)$$

In (5) A_c is defined as

$$A_c = \frac{G(N_s)\Gamma^2 a\left[e^{(\Gamma G(N_s)-\alpha_{\text{int}})z} - 1\right]}{2V\left[\Gamma G(N_s) - \alpha_{\text{int}}\right]}. \tag{6}$$

If we look at the carrier number coefficient in (5) and substitute (6) into it, then because the coefficient of the carrier number is the inverse of the carrier lifetime the effective carrier lifetime in the presence of a holding beam with power P_h will be

$$\tau_{eff} = \frac{1}{\frac{1}{\tau_e} + A_c P_h v_g}. \tag{7}$$

By comparing (1) and (7) we see that both equations have the original recovery time (the recovery time when there is no holding beam) included in them. The difference in the two equations is found by the substitution of the τ_h term in (1) with a $1/A_c P_h v_g$ term in (7). The latter term makes provision for the change in carrier number along the length of the SOA as a function of the injected light. Both equations indicate that if the holding beam's power is increased the effective recovery time decreases.

III. Numerical and analytic simulations

A numerical program was written in the C programming language, which used the SOA rate equations. The program used a constant carrier density along small increments and then changed the carrier density after each increment according to the rate equation for the change in carrier density over time. The following equation was used for the change in carrier density [2]:

$$\frac{\partial n}{\partial t} = \frac{I}{qAl} - \frac{n}{\tau_e} - \Gamma a_1 P_1 \frac{(n - n_{01})}{A\ \omega_1} - \Gamma a_2 P_2 \frac{(n - n_{02})}{A\ \omega_2}. \tag{8}$$

In (8) n is the carrier density, A is the surface area of the active region, l is the length of the active area, P_1 and n_{01} are the power and the transparency carrier density of the cw holding beam, $\hbar\omega_1$ is the photon energy of the cw holding beam, P_2 and n_{02} are the peak power and transparency carrier density of the input pulse, and $\hbar\omega_2$ is the photon energy of the input pulse. The input pulse was a Gaussian shaped pulse. The equation for the change in power looks as follows [2]:

$$\frac{\partial P}{\partial z} = (\Gamma G(N)V - \alpha_{\text{int}})P. \tag{9}$$

The maximum amplitude of the Gaussian pulse was –6,9 dBm. The Gaussian pulse was 1 psec long. The CW holding beam amplitude was simulated as a long pulse with constant amplitude of 1,1 dBm. The SOA had a 120 mA bias current. Figure 1 shows the carrier density at the end of an 800 μm SOA when these two pulses were injected into the SOA and for the case where no holding beam is present. Figure 2 shows the recovering carrier density with the Manning analytical recovery time and the recovery time of (7) also on the same graph.

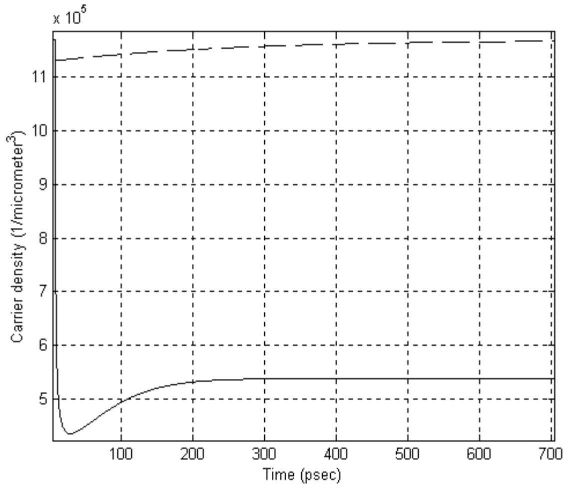

Fig. 1. Carrier density versus time at the end of an 800 μm SOA. The *dashed line* shows the case where no holding beam power is present. The *solid line* shows the case where a long constant pulse and a Gaussian pulse are simultaneously injected into the SOA.

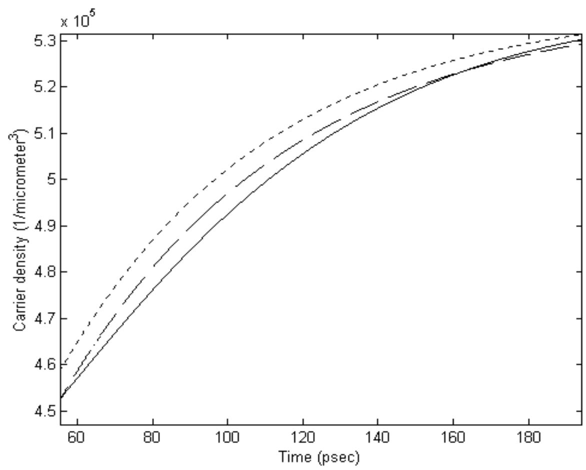

Fig. 2. Comparative plot of the numerical recovery time (*solid line*), the recovery time according to the Manning model (*dotted line*), and the recovery time according to equation (7) (*dashed line*).

In Figure 2 the improved accuracy of equation can be seen. The numerical computation showed a recovery time of roughly 260 psec. Equation (1) predicts a recovery time of 224 psec and (7) predicts a recovery time of 242 psec. Equation (7) thus shows a 7% increase in accuracy above (1). In Figure 1 the loss of small signal gain for the Gaussian pulse due to the holding beam can be seen. The largest gain in the accuracy of (7) was found when the holding beam power was large.

IV. Conclusion

We have presented a more accurate equation to analytically determine the recovery time of a SOA. Further simulations showed a larger gain in accuracy when the power of the cw holding beam was large. The recovery time provided by (1) treats the SOA as a spatial singularity. Our analytic equation takes into account that the carrier density varies along the length of the SOA's active region as a function of the injected light. The analytic equation that we proposed brought about a 7% increase in the accuracy of the predicted recovery times. Preliminary experiments also show that (7) produces a more accurate recovery time estimate.

References

[1] R.J. Manning and D.A.O. Davies, "Three-wavelength device for all-optical signal processing", *Optics Letters*, vol. 19, pp. 889-891, 1994

[2] G.P. Agrawal and N.A. Olsson, "Self-Phase Modulation and Spectral Broadening of Optical Pulses in Semiconductor Laser Amplifiers", *IEEE Journal of Quantum Electronics*, vol. 25, no. 11, pp. 2297-2306, 1989