Repetition-Rate Dependence of the Saturation Power of Gain-Clamped Semiconductor Optical Amplifiers

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***Abstract*—We show theoretically that, when using gain-clamped semiconductor optical amplifiers (GCSOA's) for the amplification of a train of pulses, the saturation power of the GCSOA's strongly depends on the repetition rate of the pulse train. This saturation power is 3 dB higher at very high repetition rates than at low repetition rates. It reaches a minimum for intermediate repetition rates, where it can even be 6 or more decibels smaller than the maximum saturation power level.**

***Index Terms*— Semiconductor optical amplifiers, small-signal analysis, time-domain analysis.**

I. Introduction

Gain-clamped semiconductor optical amplifiers (GC-SOA's) are capable of providing a relatively signal independent gain and are therefore very attractive as low crosstalk switches [1] or as amplifiers with reduced intermodulation distortion [2], [3]. When used as switches (or gates) they also can provide very high on–off ratios, while at the same time giving loss compensation.

The gain clamping has its origin in laser operation at a wavelength far away from the signal wavelengths due to a wavelength selective feedback. Because of it, only weak effects such as gain suppression and dynamic carrier density variations can contribute to the crosstalk, which remains low. However, this changes drastically when laser operation is no longer possible, i.e., when the signal power is becoming too large. In this case, strong gain saturation and hence large crosstalk are obtained.

The power independence of the gain therefore only exists up to a certain value (the saturation power) for the input signal. Beyond the saturation power, crosstalk, and distortion increase severely and hence this power determines the dynamic range of the amplifiers operation.

We will show that, when a train of pulses is used as input to such amplifiers, the dynamic range depends on the repetition rate and is 3 dB larger at high repetiton rates than at low repetition rates. In general however, over 6-dB variation in dynamic range with repetition rate is observed. At high repetition rates, the maximum saturation value for the output power is little dependent on the device parameters and is a simple function of the difference between bias and threshold current.

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A larger dynamic range obviously has several advantages and allows a more relaxed system design.

II. Amplifier Model

We assume that the GCSOA is composed of an active section surrounded on each side by DBR sections. Spatial-hole burning (SHB) is of little influence in such a structure and we can therefore use a simple rate equation model for the GCSOA. With S_l and S_a the average photon densities of the laser field and the amplifier field, respectively, and N the average carrier density in the active layer, the rate equations are

$$\frac{dS_l}{dt} = \left[G_l - \frac{1}{\tau_p}\right]S_l$$
$$\frac{dN}{dt} = \frac{\Delta I}{qV} - G_l S_l - G_a S_a \quad (1)$$

with

$$G_{l,a} = G'_{l,a}(N - N_{t(l,a)})[1 - \varepsilon_0 S_{l,a} - \varepsilon_l S_{a,l}]$$

in which ΔI is the difference between bias and threshold current, τ_p the photon lifetime, V is the volume of the active layer, ε_0 the self gain suppression and ε_1 the cross gain suppression coefficient. $G'_{l,a}$ is the differential gain and $N_{t(l,a)}$ is the transparency carrier density at the wavelength of the lasing mode and the signal respectively. As input signal we used raised cosine pulses of the form $S_a(t) = S_{a0}[1 + \cos(\Omega t)]$, with Ω/π being the repetition rate.

The rate equations have been solved both numerically and analytically by expanding S_l and N in a static and a time harmonic part (e.g., $S_l = S_{l0} + S_{l1}\cos(j\Omega t + \phi_1)$. A perturbation analysis, in which higher harmonics are neglected, has been used to determine the time harmonic parts in the last case. The validity of this approximation and of the use of a lumped amplifier model will be discussed later.

Saturation of the GCSOA occurs when gain clamping can no longer be maintained. In a real GCSOA, as in any laser, there is a gradual transition between a state where the power in the lasing mode consists of amplified spontaneous emission, with little or no gain clamping, to a state where the output in the lasing mode consists of coherent light, with strong gain clamping. To be able to define the saturation power, we have neglected the spontaneous emission that couples into the lasing mode. This approximation, also used to calculate the threshold current in numerical laser models, implies a sudden transition between the gain-clamped state and the saturated state as illustrated in Fig. 1. With this approximation, we are

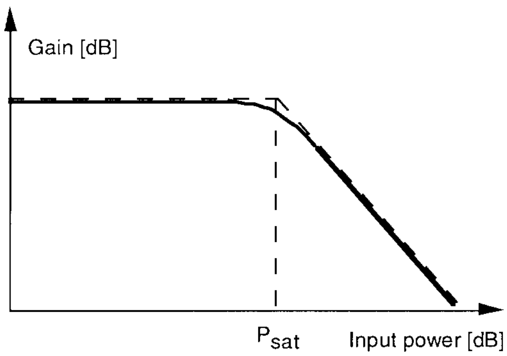

Fig. 1. Typical gain versus signal input power characteristic: real characteristic (———) and approximation (– – –) used to define the saturation power where the spontaneous emission coupling into the laser mode is neglected.

able to define the saturation power as the input power of the pulses for which the power in the lasing mode reaches zero (or for which gain clamping no longer exists). This is the case when either $S_{l0} = 0$ or $S_{l1}/S_{l0} = 1$. From the perturbation analysis, it follows that $S_{l1}/S_{l0} = 1$ if

$$\frac{S_{a0}^2\left[(\varepsilon_1 G_l)^2\Omega^2 + G_a^2 G_l'^2\left(1+\frac{\varepsilon_1}{G_a'}\frac{\partial R}{\partial N}+\left(\varepsilon_1\frac{G_l G_a'}{G_a G_l'}-\varepsilon_0\right)S_{a0}\right)^2\right]}{\left[(G_l G_l' S_{l0}-\Omega^2)^2+\Omega^2\left(\frac{\partial R}{\partial N}+\varepsilon_0 G_l S_{l0}+G_l' S_{l0}+G_a' S_{a0}\right)^2\right]} = 1 \quad (2)$$

with $\partial R/\partial N$ the differential spontaneous carrier recombination, which can be expressed in terms of the monomolecular (A), the bimolecular (B) and the Auger (C) recombination coefficient as

$$\frac{\partial R}{\partial N} = A + 2BN + 3CN^2. \quad (3)$$

One can see that at very high repetition rates ($\Omega \gg 1$) the left hand side of (2) is always smaller than one and for such repetition rates the saturation power is found where $S_{l0} = 0$. At very low repetition rates, the equation reduces to $G_a S_{a0} \approx G_l S_{l0}$. From the static carrier density equation

$$\frac{\Delta I}{qV} = G_l S_{l0} + G_a S_{a0} \quad (4)$$

one finds for the saturation power in both limiting cases

$$S_{a0}^{\max} = \frac{\Delta I}{2G_a qV}, \qquad \text{for} \quad \Omega \to 0,$$
$$S_{a0}^{\max} = \frac{\Delta I}{G_a qV}, \qquad \text{for} \quad \Omega \to \infty. \quad (5)$$

Hence, at very high repetition rates a 3-dB improvement in saturation power as compared to very low repetition rates results. The repetition rate at which this regime starts can be found by substituting $S_{l0} = 0$ and $G_a S_{a0} = \Delta I/qV$ in (2). Neglecting $\varepsilon_1 G_l G_a'/G_a G_l' - \varepsilon_0$, one finds for Ω

$$\Omega^4 + \Omega^2\left[\left(\frac{\partial R}{\partial N}+\frac{G_l'\Delta I}{G_l qV}\right)^2 - \left(\frac{\varepsilon_1 G_l \Delta I}{G_a qV}\right)^2\right] - \left(\frac{G_l'\Delta I}{qV}\right)^2\left(1+\frac{\varepsilon_1}{G_a'}\frac{\partial R}{\partial N}\right)^2 = 0. \quad (6)$$

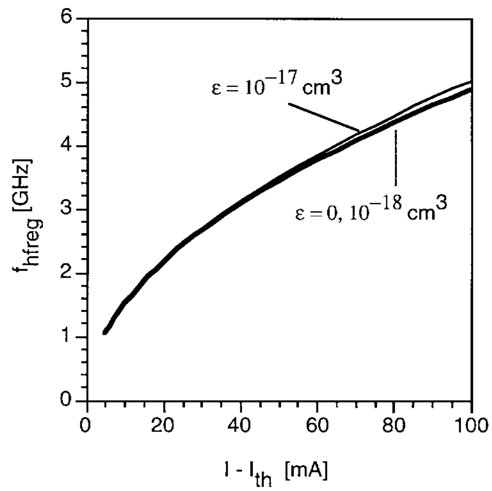

Fig. 2. Frequency where the high-frequency regime starts versus ΔI.

III. Numerical Results

In the numerical analysis, we have used the following parameters: $V = 500\ \mu\text{m}^3$, $G_l = (1/\tau_p) = 6\ 10^{11}\ \text{s}^{-1}$, $\partial R/\partial N = 2.5\ \text{ns}^{-1}$, $G_l' = 7.5\ 10^{-7}\ \text{cm}^3/\text{s}$ and $G_a' = 1.06\ 10^{-6}\ \text{cm}^3/\text{s}$. The gain compression factor $\varepsilon = \varepsilon_0 = \varepsilon_1$ has been varied.

The frequency f_{hfreg} where the hf-regime starts is shown in Fig. 2 as a function of ΔI for different ε values. This frequency is almost independent of ε and from (6) one can see that it is very well approximated by $\Omega_{\text{hfreg}} = 2\pi f_{\text{hfreg}} = (G_l'\Delta I/qV)^{0.5}$.

The saturation power itself is shown as a function of the frequency in Fig. 3 for different values of ε and ΔI. One can see that at intermediate frequencies or repetition rates, a severe decrease of the saturation power can result. Just before f_{hfreg}, the saturation power reaches a minimum value that can be as much as 8–9 dB below the hf-value. The minimum value itself however depends significantly on the gain suppression. The repetition rate where this minimum occurs corresponds with the frequency where the optical modulation response is maximum. Indeed, from the static carrier density equation one finds that the minimum value of S_{a0} is obtained if S_{l0} is maximum and in this region the saturation is determined by the condition $S_{l1}/S_{l0} = 1$. Hence, the minimum saturation power is found where S_{l1} is maximum.

From the maximum value of S_{a0}, the maximum saturation value for the output power P_{out} at high repetition rates can be found as (with $P_{\text{out}} \gg P_{\text{in}}$):

$$P_{\text{out}}^{\max} = \frac{\text{hf}}{q}\Delta I\frac{G_a - \alpha_{\text{int}} v_g}{G_a} \quad (7)$$

with α_{int} the internal loss and v_g the group velocity. Hence, if the internal loss is very small compared with the modal gain, the saturation value for the output power is equal to hf/q times the difference between bias and threshold current.

IV. Discussion

In our analysis, we have made use of a lumped amplifier model. The error introduced by this approximation is easily

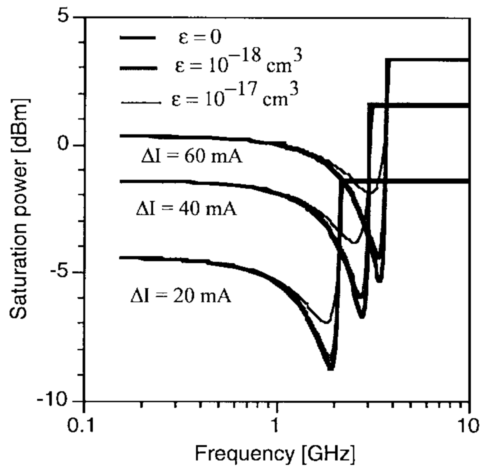

Fig. 3. Saturation input power versus frequency for different values of ε and ΔI.

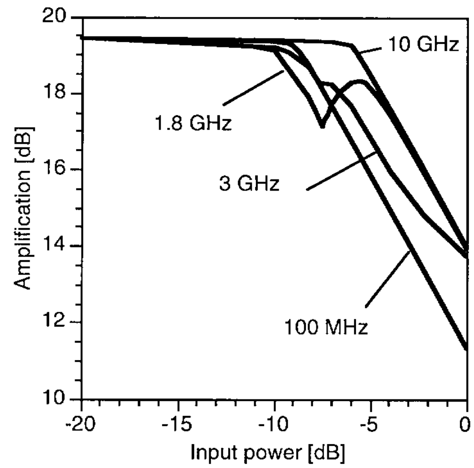

Fig. 4. Gain versus signal input power for different repetition rates as obtained with a longitudinal time-domain model for $\Delta I = 8$ mA.

estimated by noticing that spatial variations could be included in the analysis by adding an extra gain suppression to the stimulated emission term $G_a S_a$ in the carrier density equation [4]. The influence of such a gain suppression can be estimated from Fig. 3. It has been shown before however that spatial variations are not important in the analysis of semiconductor optical amplifiers as long as the intensities are averaged [5].

The error introduced by neglecting the higher harmonics in the analysis is primarily caused by neglecting the influence from the product of two cosines on the steady-state values. However, this influence is only important at high frequencies or repetition rates. Therefore, it can affect the dips seen in Fig. 2. The results for $\Omega > \Omega_{\rm hfreg}$ are of course not affected since $S_{l0} = S_{l1} = 0$ in this case.

A more accurate analysis of the repetition rate dependence of the saturation power has been done using a large signal, time-domain analysis with a longitudinal laser model. The results for different repetition rates are shown in Fig. 4 for a bias current that is 8 mA above the bias current. This figure clearly shows the phenomena predicted by our analytical analysis. The saturation power is 3 dB higher at very high frequencies than at very low frequencies and is very low for 1.8 GHz. One can also see that the low saturation power at 1.8 GHz is due to the relaxation oscillations of the laser mode.

V. Conclusion

We have shown that the saturation power of a GCSOA strongly depends on the frequency or repetition rate of the amplified signal. It is 3 dB higher at very high frequencies than at very low frequencies, but it can decrease substantially below the low frequency value at intermediate frequencies. The maximum saturation output power is proportional with the difference of bias and threshold current, but is little or not dependent on the device parameters.

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