Modeling and Optimization of
Vertical-Cavity Semiconductor Laser Amplifiers

Joachim Piprek*, Staffan E. Björlin, and John E. Bowers

Electrical and Computer Engineering Department
University of California at Santa Barbara, Santa Barbara, CA 93106

ABSTRACT

We present detailed yet largely analytical models for gain, optical bandwidth, and saturation power of vertical-cavity laser amplifiers (VCLAs) in reflection and transmission mode. VCLAs are potential low-cost alternatives to in-plane laser amplifiers and they have the inherent advantage of polarization insensitivity, high fiber coupling efficiency, and low noise figure. Simple formulas for the optical gain-bandwidth product are derived which are valid for any type of Fabry-Perot amplifier. Our saturation model is based on rate equations for electrons and holes. It considers a sub-linear material gain, gain enhancement by the standing wave effect, Auger recombination, defect recombination, and spontaneous emission. Common linear approximations are avoided to correctly predict performance limits. Excellent agreement with measurements on novel 1.3-micron VCLAs is obtained. The models are used to analyze device performance and to investigate optimization options. With reduced top mirror reflectivity and increased pump efficiency, substantial and simultaneous improvements of optical bandwidth and saturation power are predicted without sacrificing gain. Parameter plots are given which allow for an easy exploration of the VCLA design space, matching desired performance goals with the required mirror reflectivity and pump current.

Keywords: Semiconductor optical amplifiers, Fabry-Perot resonators, optical resonators, optical filters, surface-emitting lasers, optical fiber devices, quantum well devices, optical saturation, semiconductor device modeling, nonlinear equations

1. INTRODUCTION

Vertical-cavity laser amplifiers (VCLAs) are the topic of increasing interest. They are potential low-cost alternatives to in-plane SLAs and they have the inherent advantage of polarization insensitivity, high fiber coupling efficiency, and low noise figure. Two-dimensional arrays of VCLAs are attractive for parallel applications. Several groups have fabricated VCLAs based on GaAs [1] or InP [2] [3]. We have recently demonstrated the first vertical-cavity amplifiers operating at 1.3 \( \mu \)m wavelength [4], which are desirable for fiber optic applications. Commercial 1.3 \( \mu \)m vertical-cavity lasers (VCLs) are already in production [5]. Those optically pumped VCLs use GaAs / InP wafer fusion to combine InP based gain regions with highly reflective AlGaAs / GaAs mirrors.

Figure 1 shows the refractive index profile in the center part of our double-fused, planar, and undoped vertical-cavity amplifier. Two 1.3 \( \mu \)m AlAs/GaAs distributed Bragg reflectors (DBRs) with 25 (bottom) and 13 (top) periods, respectively, are fused to an InP based active region. The DBR spacing is about 1 \( \mu \)m, 2.5 times the internal signal wavelength. The active region contains 3 stacks of 7 compressively strained 6.3 nm thick InAs\(_{0.5}\)P\(_{0.5}\) quantum wells (QWs) and strain-compensating In\(_{0.8}\)Ga\(_{0.2}\)P barriers. The 3 multi-quantum well (MQW) stacks are placed at the 3 central peaks of the standing optical wave (Fig. 1). The 21 quantum wells are designed to have maximum optical gain at the signal wavelength (Fig. 2). The quantum wells are also the only layers in our structure to allow for band-to-band absorption of the 980 nm pump laser beam. The pump beam is focused through the bottom GaAs substrate to a small spot of about 8 \( \mu \)m diameter. The input signal is generated by a tunable 1.3 \( \mu \)m laser and it is coupled in and out through the front DBR using a circulator (signal spot size 4 \( \mu \)m). Focusing and matching both the light beams is crucial to achieve sufficient optical gain in our planar device. 1.3 \( \mu \)m anti-reflection coating was applied to the GaAs substrate to avoid interference from backside signal reflection. The output signal is monitored by an optical spectrum analyser. With 13 front mirror periods, the best performance parameters measured

* Correspondence: Email: piprek@ece.ucsb.edu, WWW: http://eci.ucsb.edu/~piprek, Telephone: 805-893-4051
at different pump levels are 9.4 dB fiber-to-fiber gain, 90 GHz optical bandwidth (0.5nm), and -6.1 dBm saturation output power.

To improve the performance of present VCLAs, a more detailed understanding of design options is highly desirable. The design theory for Fabry-Perot in-plane SLAs is well developed (see, e.g., [6]), however, some limiting factors are often neglected, like the sub-linear increase of the material gain with rising carrier density. Moreover, vertical-cavity devices exhibit important differences. The short vertical cavity allows for only one longitudinal mode. Thin active layers are passed in vertical direction and the single pass gain is very small. However, the material gain may be enhanced by up to factor two if the active layers are placed at the peaks of the standing optical wave. Highly reflective DBRs are required for reasonable amplifier gain. Light penetration into these mirrors substantially enlarges the effective cavity length (Fig. 1) which needs to be considered in Fabry-Perot type models. There are very few publications on the design theory of VCLAs [7] [8]. Those papers neglect essential properties of vertical-cavity amplifiers and do not validate their calculations by measurements.

In the following, we derive a detailed yet largely analytical one-dimensional VCLA model both for operation in reflection mode (signal output through top DBR) and transmission mode (signal output through bottom DBR). The model for gain and bandwidth is based on the Fabry-Perot resonator approach and the saturation model uses single mode rate equations. Measured characteristics from [9] are employed for validation as well as for the extraction of internal device parameters. We will show that design optimization can lead to major performance improvements.

2. GAIN AND BANDWIDTH

A common modeling approach to vertical cavity lasers is the replacement of the DBRs by hard mirrors of the same reflectivity which are separated by an effective cavity length $L_e$ [10]. This way, we can start with the well known gain formulas of Fabry-Perot amplifiers ($G_R$ - reflection mode, $G_T$ - transition mode) [7]

$$G_R = \frac{\left(\sqrt{R_f} - \sqrt{R_b} G_s\right)^2 + 4\sqrt{R_f R_b} G_s \sin^2 \Phi}{\left(1 - \sqrt{R_f} R_b G_s\right)^2 + 4\sqrt{R_f R_b} G_s \sin^2 \Phi}$$

(1)
with the front mirror reflectivity $R_f$, the back mirror reflectivity $R_b$, the single pass gain $G_s$, and the single pass phase detuning $\Phi$. The maximum gain is achieved with $\Phi = 0$, when the signal wavelength is identical to the Fabry-Perot resonance. VCLAs exhibit much smaller values $G_s$ and larger reflectivities than in-plane devices. For VCLAs, the peak reflectivity of lossless DBRs with $m$ periods ($2m$ layers) is given by [11]

$$R_{DBR} = \left( \frac{1 - qp^{2m-1}a}{1 + qp^{2m-1}a} \right)^2$$

using the low-to-high refractive index ratios of the two DBR layers ($p$), as well as at the first ($q$) and the last ($a$) DBR interface. Assuming refractive indices of 3.45 (GaAs) and 2.89 (AlAs), we calculate $R_f = 0.985$ and $R_b = 0.999$ for our device. Absorption or diffraction within the mirror reduces the reflectivity [12]. The wavelength dependence of the DBR reflectivity is ignored here since the reflection bandwidth of typical DBRs is much larger (about 100 nm in our case) than the amplifier bandwidth and the cavity resonance wavelength $\lambda_c$ is assumed identical to the DBR center wavelength. Our one-dimensional model also neglects the transversal optical mode structure. Resonance wavelengths differ slightly among transversal modes. The phase $\Phi$ in Eqs. 1-2 gives the deviation of the signal wavelength $\lambda$ from $\lambda_c$.

$$\Phi = 2\pi n_c L_c \left( \frac{1}{\lambda} - \frac{1}{\lambda_c} \right)$$

with the cavity refractive index $n_c$. The effective cavity length $L_c$ is larger than the DBR distance $L_m$ and it includes the phase penetration depths $L_f$ and $L_b$ into front and back DBR, respectively ($L_c = L_f + L_m + L_b$). The phase penetration depth $L_p$ of a lossless DBR at center wavelength $\lambda_c$ is given by [13]

$$L_p = \frac{\lambda_c}{4n_c} \times q \times \frac{1}{1 - p} \times \frac{\left(1 - a^2 p^{2m-1}\right) \left(1 - p^{2m}\right)}{1 - q^2 a^2 p^{4m-2}}$$

With $n_i = 3.2$, the DBR penetration depth in our device is about 585 nm, resulting in the effective cavity length $L_c = 2.2 \mu$m (Fig. 1). Due to the high index contrast, AlAs/GaAs DBRs exhibit smaller penetration depths than mirrors grown on InP. The cavity refractive index $n_i$ is obtained by averaging over all layers between the two DBRs. Typically, it is somewhat higher than the refractive index of the spacer material (InP) at the target wavelength, however, it can be affected by the quantum well carrier density as well as by device heating.

The remaining parameter in Eqs. 1-2 to be discussed is the single pass signal gain $G_s$. Assuming laterally uniform material properties across the signal spot, the single pass gain in a VCLA is calculated from the active region material gain $g$ by

$$G_s = \exp[\xi g L_a - \alpha_c L_c]$$

with the gain enhancement factor $\xi$ ($\xi < 2$), the total thickness $L_a$ of all quantum wells, and the average cavity loss coefficient $\alpha_c$. Gain enhancement results from the placement of the active region(s) at the peak(s) of the standing optical wave with [14]

$$\xi = 1 + \frac{\sin \left(2\pi n_c L_{MQW} / \lambda_c \right)}{2\pi n_c L_{MQW} / \lambda_c}$$
(L_MQW - thickness of each MQW stack). We calculate $\xi = 1.75$ for our periodic gain structure (Fig. 1). Computation of the quantum well material gain $g$ is the main challenge of VCLA modeling. The optical gain depends on the QW carrier density $N$, the signal wavelength $\lambda$, the temperature $T$, and the photon density $S$. Assuming $\lambda = \lambda_c$, room temperature, and relatively low photon densities, the quantum well gain can be approximated by [10]

$$g(N) = g_o \ln\left(\frac{N + N_s}{N_{tr}}\right)$$

(8)

with the transparency carrier density $N_{tr}$, and the fit parameters $g_o$ and $N_s$. We calculate the optical gain of our strained MQWs utilizing an advanced laser simulation software [15]. The conduction bands are assumed to be parabolic and the non-parabolic valence bands are computed by the 4x4 $kp$ method including valence band mixing [16]. The gain calculations employ a Lorentzian broadening function with 0.2 ps intraband relaxation time. The resulting gain spectra are shown in Fig. 2 for four different carrier densities. Strong absorption is calculated at the pump wavelength and the gain is maximum at the signal wavelength. The spectral width of the gain is on the order of 100 nm. The carrier density dependence at the signal wavelength 1.32 $\mu$m can be fitted by Eq. 8 using the parameters $g_o = 1580$ cm$^{-1}$, $N_{tr} = 1.1 \times 10^{18}$ cm$^{-3}$, and $N_s = -0.63 \times 10^{18}$ cm$^{-3}$ for our quantum well active region.

The VCLA bandwidth is mainly restricted by the linewidth of the Fabry-Perot modes. From Eqs. 1-2 one can easily obtain the following formulas for the amplifier bandwidth in reflection and transmission mode, respectively

$$\Delta f_R = \frac{c}{\pi n_e L_c} \times \arcsin\left\{4 \sqrt{R_f R_b G_s} \left[\left(1 - \sqrt{R_f R_b G_s}\right)^2 - 2 \left(\sqrt{R_f} - \sqrt{R_b} G_s\right)^2\right]\right\}^{-1/2}$$

(9)

$$\Delta f_T = \frac{c}{\pi n_e L_c} \times \arcsin\left\{4 \sqrt{R_f R_b G_s}^{-1} \left(1 - \sqrt{R_f R_b G_s}\right)^2\right\}^{1/2}$$

(10)

(c - vacuum light velocity). These formulas give the full width at half maximum (-3dB). In general, the bandwidth decreases as the peak gain increases. The square root of the peak gain times the bandwidth give a figure of merit that is practically constant (gain-bandwidth product). The threshold condition and the approximation $\sin(x) = x$ (for small $x$) leads to the simple formulas

$$\sqrt{G_R^0} \Delta f_R = \frac{c}{2 \pi n_e L_c} \left(\frac{1}{\sqrt{R_f}} - \sqrt{R_f}\right)$$

(11)

$$\sqrt{G_T^0} \Delta f_T = \frac{c}{2 \pi n_e L_c} \left(\frac{1 - R_f}{\sqrt{R_f R_b}}\right)$$

(12)

These equations are valid for any Fabry-Perot amplifier and their results are identical for symmetrical devices ($R_f = R_b$). In the reflection case, Eq. 11 is restricted to gain values well above 3dB since the initial reflection causes a singularity of Eq. 9. Remarkably, the gain-bandwidth product in reflection mode does not depend on the bottom reflectivity $R_b$ and gain-bandwidth measurements can be used to verify the front reflectivity $R_f$ or the optical cavity length $n_e L_c$. Figures 3 and 4 plot the gain-bandwidth product as function of the output mirror reflectivity for reflection and transmission mode, respectively. The dots in Fig. 3 give measured results of our 1.3$\mu$m VCLAs which confirm our model. Lower reflectivity gives higher bandwidth in both cases. The reflection mode curve crosses transmission mode curves for symmetric devices ($R_f = R_b$). This leads to the intuitive result that the transmission mode gives a higher gain-bandwidth product than the reflection mode if $R_b < R_f$ (and vice versa).
3. SATURATION POWER

High signal power results in gain saturation due to carrier depletion within the active layers. We use steady-state rate equations for carriers and photons to describe the saturation effect. In VCLAs, only a single longitudinal mode needs to be considered. Equation 13 summarizes all physical mechanisms which affect the average carrier density $N$ within the active layers. The first term describes external pumping by an effective current density $j_p$ which is related to the optical pump power ($e$ - electron charge). We shall use $j_p$ as fit parameter since our optical pump efficiency is hard to calculate. The carrier recombination rate $R(N)=AN+BN^2+CN^3$ in Eq. 13 includes defect recombination (discussed below), spontaneous photon emission ($B=10^{10}$ cm$^3$/s), and Auger recombination ($C=2\times10^{-29}$ cm$^6$/s) - material parameters are given for typical 1.3µm InGaAsP active layers [17]. In linear approximation, the carrier lifetime $\tau_c$ is often employed as $R(N)=N/\tau_c$. However, in long-wavelength amplifiers, Auger recombination may cause significant deviations from the linear approximation. The last term in Eq. 13 gives the stimulated recombination rate ($v_g$ - photon group velocity, $S$ - average photon density). The gain enhancement factor $\xi$ accounts for the standing wave effect. A linear gain approximation $g(N) = \gamma(N-N_p)$ is often used which is appropriate for small carrier densities. We avoid linear approximations here to find more realistic performance predictions for strong pumping and large carrier densities.

$$\frac{dN}{dt} = \frac{j_p}{eL_a} - (AN + BN^2 + CN^3) - \xi g(N) v_g S = 0 \quad (13)$$

$$\frac{dS}{dt} = (1 - R_f) \frac{\lambda_c}{hc} \frac{P_m}{A_m L_c} + \xi \Gamma g(N) v_g S + \beta \Gamma BN^2 - (\alpha_c + \alpha_m) v_g S = 0 \quad (14)$$

![Fig. 3: Square-root of gain times optical bandwidth vs. output mirror reflectivity in reflection mode as calculated from Eq. 11 (dots - measurements).](image)

![Fig. 4: Square-root of gain times optical bandwidth vs. output mirror reflectivity in transmission mode as calculated from Eq. 12.](image)
The second rate equation summarizes all physical mechanisms that affect the average photon density $S$ (Eq. 14). The first term describes the photon density increase resulting from the signal power $P_{in}$ per area $A_{in}$ entering through the front mirror ($h \cdot \text{Planck's constant}$). The next two terms represent stimulated and spontaneous photon generation rates, respectively. The coefficient $\beta$ gives the fraction of spontaneously emitted photons that is coupled into the signal mode. In our case, $\beta$ is about 0.01 [10]. The last term in Eq. 14 represents all photon losses, including cavity absorption and scattering ($\alpha_{c}=15 \text{ cm}^{-1}$) as well as photon transmission through the mirrors with

$$\alpha_{m} = \frac{1}{L_{c}} \ln \left[ \frac{1}{\sqrt{R_{f} R_{g}}} \right]$$

(15)

For our device we calculate $\alpha_{m} = 36 \text{ cm}^{-1}$. Eq. 14 delivers the equilibrium photon density

$$S_{o} = \frac{1}{v_{g}} \left( \beta \xi BN^{2} + \frac{\lambda_{c} (1 - R_{f}) P_{in}}{hCA_{m} L_{c}} \right) \times (\alpha_{m} + \alpha_{c} - \xi \Gamma g(N))^{-1}$$

which becomes very large near lasing threshold. The threshold is defined by $\xi \Gamma g(N) = \alpha_{m} + \alpha_{c}$ which is equivalent to $R_{f} R_{g} G_{T}^{2} = 1$. Alternatively, the average photon density $S_{c}$ in amplifiers may be calculated from the Fabry-Perot approach [8] [18] which results in significantly larger numbers. Both methods are known to give different results [6] and we find full agreement with the measurements only by using the rate equation approach.

Introducing Eq. 16 into Eq. 13, an implicit equation for the equilibrium carrier density $N_{o}$ is obtained which is rather difficult to solve. This situation can be simplified by looking at two specific steady-state cases which are of special interest with amplifiers. In the unsaturated case with small input power $P_{in}$, the photon density $S_{o}$ is low and the stimulated recombination in Eq. 13 is negligibly small compared to $R(N)$. In other words, carrier density $N_{o}$, material gain $g(N_{o})$, single pass gain $G_{s}$ as well as the amplifier gain ($G_{T}$, $G_{R}$) are independent on the input power which is desirable for typical amplifier operation. However, with increasing input power, the stimulated recombination rate rises and the carrier density eventually starts to decrease. This results in lower material gain and lower amplifier gain. The saturation input power $P_{in,sat}$ is reached when the amplifier gain drops to half its maximum value. Signal input and output power at saturation are a key performance parameters of amplifiers and they can be calculated analytically from above equations without any simplification, as shown in the following.

First, the unsaturated carrier density $N_{u}$ is obtained from the weak signal equilibrium limit of Eq. 13 ($S=0$) which gives a simple cubic equation having the solution

$$N_{u} = \left[ \frac{B}{3C} \right]^{1/3} - \frac{u}{3} \left[ \frac{B}{3C} \right]^{1/3} - \frac{w}{2} \left[ \frac{B}{3C} \right]^{1/3} - \frac{B}{3C}$$

(17)

$$u = \frac{2}{27} \left( \frac{B}{C} \right)^{3} - \frac{BA}{3C^{2}} - \frac{j_{p}}{eL_{c} C}, \quad w = \frac{A}{C} - \frac{1}{3} \left( \frac{B}{C} \right)^{2}$$

Using Eq. 1 and 2, the carrier density $N_{u}$ leads to the unsaturated peak gain $G_{Ru}$ and $G_{Tu}$, respectively. The saturation carrier densities for reflection and transmission mode are then given by
From these saturation carrier densities we obtain the saturation input power using Eq. 13 and Eq. 16

\begin{align*}
N_{Rs} &= (Ntr + Ns) \exp \left[ \frac{\alpha_c}{\xi \Gamma g_o J} \left( \sqrt{0.5 \times G_{Ru} + R_f} \right) \sqrt{R_f R_b \left( 0.5 \times G_{Ru} + R_b \right)} \right] \frac{1}{\epsilon \xi \Gamma J} - N_s, \quad \text{(18)} \\
N_{Ts} &= (Ntr + Ns) \exp \left[ \frac{\alpha_c}{\xi \Gamma g_o J} \left( r - \sqrt{r^2 - \frac{1}{R_f R_b}} \right) \right] \frac{1}{\epsilon \xi \Gamma J} - N_s, \quad \text{(19)} \\
r &= \frac{G_{Tu} \sqrt{R_f R_b} + (1 - R_f)(1 - R_b)}{G_{Tu} R_f R_b}
\end{align*}

From these saturation carrier densities we obtain the saturation input power using Eq. 13 and Eq. 16

\begin{align*}
P_{\text{in, sat}} (N_{\text{sat}}) &= \frac{hc A_m L_c}{\lambda_c (1 - R_f)} \left[ \left( \frac{j_p}{e L_a} - R(N_{\text{sat}}) \left( \frac{\alpha_m + \alpha_c}{\xi g (N_{\text{sat}})} - \Gamma \right) - \beta \Gamma BN_{\text{sat}}^2 \right) \right] \quad \text{(20)}
\end{align*}

with \(N_{\text{sat}} = N_{Rs}\) or \(N_{\text{sat}} = N_{Ts}\) for reflection or transmission mode, respectively. The saturation output power for both modes is

\begin{align*}
P^R_{\text{out, sat}} &= P_{\text{in, sat}} (N_{Rs}) \frac{G_{Ru}}{2} \\
P^T_{\text{out, sat}} &= P_{\text{in, sat}} (N_{Ts}) \frac{G_{Tu}}{2} \quad \text{(21)}
\end{align*}

To validate the model and to specify internal parameters, we simulate measured device characteristics. The dots in Fig. 5 represent measured data for the reflection gain as function of input power. To simulate this curve, the steady state carrier rate equation is solved numerically using the average photon density given by Eq. 16. Several internal parameters are involved in this simulation which are not exactly known. We consider both the effective pump current density \(j_p\) and the defect recombination parameter \(A\) as most critical and vary both numbers to find agreement with the measurement in Fig. 6. The fit gives \(j_p = 540 \text{ A/cm}^2\) and the defect recombination lifetime \(\frac{1}{A} = 15 \text{ ns which is a measure of active region growth quality. With low input power, we extract } 1.18 \times 10^{18} \text{ cm}^{-3} \text{ average QW carrier density and 5 ns carrier lifetime. However, the pumping efficiency seems to be quite low, the effective injection current per quantum well is only } 26 \text{ A/cm}^2 \text{ leaving room for substantial improvement. From the calculated QW absorption coefficient } \alpha_{qw} = 5000/\text{cm at } \lambda_p = 980 \text{ nm (Fig. 2), we estimate about 30 times higher pump current densities}

\begin{align*}
j_p &= e L_a \frac{T_p P_p}{A_p} \times \frac{\lambda_p}{h c} \times \frac{1 - \exp(-\alpha_{qw} L_a)}{L_a} \quad \text{(22)}
\end{align*}

assuming a pump beam transmittance of \(T_p \sim 1\) (pump power \(P_p = 150 \text{mW}, \text{ pump area } A_p = 50 \mu \text{m}^2\)). The poor pumping efficiency is attributed to optical losses as well as to lateral carrier spreading which is not yet included in our model. The pump area is about 4 times larger than the signal spot. Better matching and higher pump power are expected to allow for significant performance improvements. Fig. 5 also predicts the performance with lower top mirror reflectivity. The input saturation power increases as the number of top mirror periods decreases. The decay in reflection gain can easily be compensated for by stronger pumping (dashed line in Fig. 5).
Based on Eqs. 21, the relation between peak gain and output saturation power is shown in Figs. 6 and 7 for a wide range of output DBR periods. The lines are generated by varying the pump current, starting at the transparency current on the left and ending at the lasing threshold on the right. Thus, the QW carrier density is continuously increased along the lines. The peak gain refers to the unsaturated carrier density $N_u$ whereas the saturation power is calculated from the somewhat smaller carrier density $N_{sat}$ at saturation. With small gain ($N_u > N_{tr}$), the saturation power peaks sharply at $N_{sat} = N_{tr}$ since the material gain is zero (see Eq. 20). In other words, the rising input power stops stimulated recombination before saturation is reached. From that point on, the input saturation power declines steadily with stronger pumping, however, the output saturation power benefits from the rising saturation gain which can cause a flat maximum. Beyond that maximum, the saturation power drops sharply as the lasing threshold is approached. The dots in Fig. 6 represent measurements on 1.3μm VCLAs with 13 [9] and 12 [19] top mirror periods, respectively. Simulation and measurement show perfect agreement. The measured saturation power is close to its theoretical maximum for our current devices. Reducing the number of output mirror periods allows for more gain and higher saturation power, but the required pump current also rises (see Figs. 8 and 9). For example, by reducing the top mirror reflectivity of our current devices to 0.833 (6 periods), we can achieve 7 dBm output saturation power without sacrificing the 10 dB gain (Fig. 6). However, the pump current density needs to be increased to 2.35 kA/cm² (Fig. 8) which is about four times higher than with our previous experiments. This pump current gives the unsaturated carrier density $N_u = 2.5 \times 10^{18}$ cm⁻³, resulting in $g = 2200$ cm⁻¹ and $G_s = 1.05$. With 10 dB gain, the optimized device would exhibit about 420 GHz bandwidth in reflection mode (Fig. 3). This example shows how to use the figures shown to explore design options. Large bandwidths are desirable, e.g., for multiple channels whereas small bandwidths are needed in filter applications. For instance, selecting a smaller target bandwidth of 30 GHz in transmission mode at 10 dB gain (100 GHz gain-bandwidth product), we extract from Fig. 4 the required bottom DBR reflectivity to be about 0.982 (15 bottom periods for 13 top periods). This gives 2 dBm saturation power (Fig. 7) and about 700 A/cm² required pump current density (Fig. 9).

Our design figures allow for an easy exploration of the VCLA design space, matching desired performance data with the required mirror reflectivity and pump current. Figs. 3 & 4 are most general and allow for bandwidth considerations with any Fabry-Perot type amplifier. However, the curves in Figs. 6-9 are restricted to our 1.3μm active region and recalculation is required for other types of active regions.
We present a detailed model for gain, optical bandwidth, and saturation of vertical-cavity laser amplifiers. Distinctive features of vertical-cavity device physics are taken into account, like the penetration depth into the mirror and the standing wave effect on the gain. Common linear approximations for gain and carrier lifetime are avoided to reliably investigate the performance at high carrier densities. Excellent agreement with measurements on novel 1.3\,\mu m vertical-cavity amplifiers is obtained. With reduced top mirror reflectivity (6 periods) and increased pumping (2.35 kA/cm$^2$), substantial and simultaneous improvements of optical bandwidth (420 GHz) and output saturation power (7dBm) are predicted maintaining...
10 dB reflection gain. Apart from the numerical gain calculations, the model is fully analytic and easy to apply to other types of vertical-cavity semiconductor optical amplifiers.

ACKNOWLEDGEMENTS

This work was supported by the DARPA Multidisciplinary Optical Switching Technology (MOST) Center at UCSB.

REFERENCES