The optical gain lever: A novel gain mechanism in the direct modulation of quantum well semiconductor lasers

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A new gain mechanism active in certain quantum well laser diode structures is demonstrated and explained theoretically. It enhances the modulation amplitude produced by either optical or electrical modulation of quantum well structures. In the devices tested, power gains of 6 dB were measured from low frequency to frequencies of several gigahertz. Higher gains may be possible in optimized structures.

We have recently demonstrated a new technique called active-layer photomixing for producing parasitic-free modulation in a semiconductor laser.[1-3] In this technique two single-frequency laser sources are photomixed directly in the active layer of a laser diode thereby producing carrier density modulation and hence laser diode light output modulation at the difference frequency of the two sources. In this letter we describe a new optical gain mechanism that has been revealed by application of this technique to quantum well semiconductor lasers. Although described in the context of a transphotonic device, it can also be used to produce net gain in conventional current modulation of laser diodes. In the devices investigated power gains as large as 6 dB (7 dB photon number gain) have been measured for conversion of absorbed radiation to output radiation. The dynamic response of this optical gain has been observed to extend from low frequency to frequencies of several gigahertz. A theoretical explanation of the amplification process will be presented. The amplification is seen to result from an effect we call the "optical gain lever." In what follows we will discuss the experimental arrangement and the device structure, explain the effect based on a simple model, and finally discuss the experimental results in light of this simple model, including a discussion of possible approaches to enhancing the effect.

The device geometry and experimental setup are shown in Fig. 1. The low-frequency gain characteristics of three devices were measured at various bias current levels. All devices tested were buried-heterostructure GaAs lasers with a 100 Å single quantum well in an AlGaAs graded-index separate confinement heterostructure (GRINSCH). The results presented are for a device having a threshold current of 27 mA and a lasing wavelength of 850 nm, and are representative of data taken on the other devices. To gain access to the active layer for optical input a 5-μm-long opening in the metal contact adjacent to the output facet was created. The remainder of the contact was used to apply a bias current to the device. The pump laser used in the experiment is a krypton laser operating single mode at 676.4 nm. This wavelength was selected because it is not absorbed by the AlGaAs cap layer of the laser, but is absorbed by the GRINSCH structure and the quantum well (note: the cap layer is $Al_{0.5}Ga_{0.5}As$ and the GRINSCH structure varies from $Al_{0.2}Ga_{0.8}As$ to $Al_{0.5}Ga_{0.5}As$). The pump light is conveyed to the opening in the laser diode contact layer by various optical elements and alignment is facilitated using a beam-splitter to image the laser surface onto a video camera. Viewing the device as a gain element, the pump laser radiation is the input and the laser diode output radiation is the amplified output. In the present embodiment of the amplifier, a necessary feature is a wavelength shift to longer wavelengths from input to output (i.e., from krypton excitation at 676.4 nm to GaAs quantum well emission at 850 nm).

Before presenting the experimental results on optical gain, it is helpful to discuss the amplification effect theoretically. We model the active layer of the laser diode in terms of a small control region (the optically pumped region) and a slave region (the electrically pumped region) and denote quantities pertaining to each region by subscripting with a "c" or an "s." The choice of terminology will become obvious momentarily. We assume that the photon density is uniform along the length of the cavity. Even in the control region, which is most likely absorbing, this assumption is good because of the short length of this region. A small signal model based on a set of rate equations for the control region, the slave region, and the lasing mode shows that the intrinsic low-frequency optical gain (i.e., the ratio of absorbed optical input power P_i at wavelength λ_i to laser output power P_o at λ_o) is given by the expression

$$G_I = \frac{P_o}{P_i} = \frac{\lambda_i}{\lambda_o} \frac{g_c' \tau_c}{g_s' \tau_s} \frac{1 + g_s' \tau_s p}{1 + g_c' \tau_c p}, \tag{1a}$$

where, for example, τ_c is the spontaneous lifetime and g_c' is the differential gain (i.e., the derivative of gain with respect to carrier density) for the control region, and p is the photon density. (Note: the actual device gain G is given by $G = \eta G_I$, where η accounts for coupling losses associated with Fresnel reflection of the input beam and finite absorption of the input

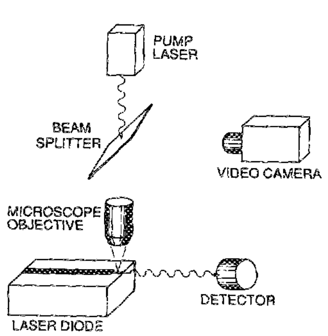

FIG. 1. Diagram of experimental arrangement.

by the active region.) In the context of electrical current modulation this expression becomes

$$G_I = \frac{P_o}{I_i} = \frac{\hbar\omega}{q}\frac{g_c'\tau_c}{g_s'\tau_s}\frac{1+g_s'\tau_s p}{1+g_c'\tau_c p}, \tag{1b}$$

where I_i is the input current, $\hbar\omega$ is the energy of lasing photons, and q is the electronic charge. Rather than presenting the detailed calculation here, a more physically intuitive model will be developed that provides an expression for the low-frequency gain of the device in agreement with the above result. The more detailed treatment of the device based on the rate equations will be presented elsewhere.[4] The intuitive model is useful in understanding the origin of the gain effect and ways to enhance it. Before proceeding with the derivation, it should be noted that an important assumption in what follows is that the modal gain (or modal loss) associated with the control region is much smaller than the modal gain of the slave region, i.e., the control region has a negligible direct effect on the lasing mode. This is always true provided the control region comprises only a small fraction of the overall cavity as is the case in the devices studied here. In situations where this is not the case, however, expressions (1a) and (1b) are modified significantly. These modifications reflect changes in output power associated with conventional saturable absorber effects in the control region and will be discussed in the more detailed treatment.

For operating points sufficiently above threshold and for quasi-steady-state operation (i.e., for frequencies well below the relaxation oscillation frequency), the overall modal gain is approximately clamped at a value determined by the cavity losses ("approximately" because spontaneous emission always accounts for a small energy input to the mode). This means that changes in the modal gain associated with one of the regions of interest in the device must be compensated by an equal and opposite change in the modal gain of the other region. For small-signal considerations we can model such a change by linearizing the gain as a function of carrier density. The requirement of gain clamping then translates into the following equation:

$$\Gamma_c g_c' \Delta n_c = -\Gamma_s g_s' \Delta n_s, \tag{2}$$

where Δn_c (Δn_s) and Γ_c (Γ_s) are the change in carrier density (assumed uniform in each region) and the optical confinement factor for the control (slave) region. The simple relation given by Eq. (2) is represented graphically in Fig. 2 and will be seen to be the basis for the measured optical gain mechanism.

To proceed it is necessary to relate the change in carrier density in each region to the appropriate input or output power. In doing this it will be necessary to model how a small-signal change in the carrier density decays in the presence of the lasing mode. This decay rate emerges naturally in small-signal calculations of the frequency response of laser diodes and is sometimes referred to as the relaxation oscillation damping rate. Its form for the control region is given by

$$\gamma_c = 1/\tau_c + g_c' p, \tag{3}$$

with a similar expression holding for the slave region.

In the control region, an input of $\lambda_i P_i / hc$ photons per second will cause an increase in the carrier recombination

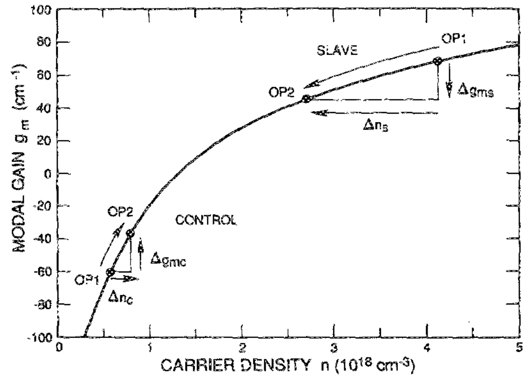

FIG. 2. Origin of the optical gain lever mechanism. A displacement along the gain curve in the control region induced by absorption of input light or an injected current causes an enhanced reaction in the slave region. Quantities plotted are modal gains (i.e., they include the confinement factor).

rate of $\Gamma_c V \Delta n_c \gamma_c$, where V is the mode volume (i.e., $\Gamma_c V$ is the control region volume), h is Planck's constant, and c is the speed of light. This steady-state balance gives the equation:

$$P_i = \Gamma_c V \Delta n_c (hc/\lambda_i)\gamma_c. \tag{4}$$

The resulting complementary decrease in the slave region carrier density [via Eq. (2)] will decrease the slave recombination rate by $\Gamma_s V \Delta n_s \gamma_s$. Since electrical pumping is constant, however, this decrease must be accompanied by an equal increase in the stimulated emission rate into the lasing mode. Equating these quantities gives the result

$$P_o = -\Gamma_s V \Delta n_s (hc/\lambda_o)\gamma_s. \tag{5}$$

If Eqs. (4) and (5) are used to replace $\Gamma_c \Delta n_c$ and $\Gamma_s \Delta n_s$ in Eq. (2), then the expression for intrinsic gain given by Eq. (1) results. Equation (1) has another interesting form. It is possible to show that for small-signal changes in the photon density the quantity $(g_c'\tau_c)^{-1}$ [or $(g_s'\tau_s)^{-1}$ for the slave region] is the saturation photon density associated with the control region.[4] Making this substitution into Eq. (1), we arrive at the equivalent form

$$G_I = \frac{P_o}{P_i} = \frac{\lambda_i}{\lambda_o}\frac{p_{\text{sat}}^s}{p_{\text{sat}}^c}\frac{1+p/p_{\text{sat}}^s}{1+p/p_{\text{sat}}^c}. \tag{6}$$

The nature of the optical gain mechanism is readily understood by this intuitive model. For simplicity consider a situation in which $\tau_c = \tau_s$ and where the photon density remains lower than the saturation density of either region. For such a case optical gain will result when g_c' is larger than g_s' as diagrammed in Fig. 2. When this happens a favorable "gain lever" effect results in which a given number of electrons produced by absorption of input light causes a larger decrease of carrier number in the slave region. The corresponding increase in the stimulated rate will then be g_c'/g_s' larger than the absorption rate of input photons. It is clear that a quantum well is an ideal gain medium in which to demonstrate this effect since the optical gain in a quantum well saturates as a result of the flat electronic density of states function in a given energy subband. The gain curve shown in Fig. 2 is, in fact, calculated for a single GaAs quantum well. The slave and control operating points selected are consistent with the device structure we have described. Note, however, that the actual Δg_m's are normally much smaller owing

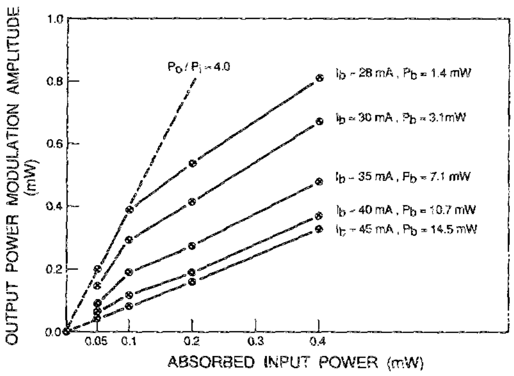

FIG. 3. Change in total output power (i.e., both facets) vs absorbed optical input power at several slave region bias levels.

to the smallness of Γ_c. We have assumed a large Γ_c in the figure purely for illustrative purposes.

In considering the structure of Eqs. (1a) and (1b), it is apparent that another way to realize gain is to arrange for the carrier lifetime to be larger in the control region as compared to the slave region. When this occurs, larger changes in carrier density are possible for a given input power, thus leading to greater influence over the slave region by the control region. Interestingly, this lifetime-related gain mechanism is also responsible for the ultimate saturation of the gain lever mechanism at high photon densities. For high photon densities the stimulated-emission component of the recombination rate modifies the effective carrier lifetime in a way that precisely counteracts the original low-power gain lever effect. This ultimately produces a power conversion dictated by a simple exchange of high-energy input photons for low-energy output photons. Another saturation mechanism is also possible in this device. This is saturation related to band filling in the control region at high input power. Both of these saturation mechanisms are apparent in the devices studied as described below.

Figure 3 shows the measured change in total output power versus the absorbed input power at several bias levels. The bias level points are given in terms of both total output power and in terms of bias current to the slave region. Notice that the characteristics indicate saturation with increasing bias level as predicted above. It was found that the characteristics did not change for bias levels beyond $I = 45$ mA. From this observation and in accordance with the earlier discussion of high-power saturation, we conclude that the $I = 45$ mA characteristic reflects a situation in which $G = \eta\lambda_i/\lambda_o$ (and equivalently $G_I = \lambda_i/\lambda_o = 0.79$). On the basis of this result we estimated the net absorption of input light to be $\eta = 20\%$. This is consistent with estimates of Fresnel reflection from the surface (30%) and estimates of absorption by the GRINSCH structure (30%). (Note that the GRINSCH structure is an important part of this device since it provides most of the input absorption and then efficiently channels carriers into the quantum well.)

Now consider the low-power characteristic ($I = 28$ mA). For low input levels the response is linear up to output powers of 400 μW and the observed intrinsic power gain is 6 dB (7 dB in terms of a photon number gain). Beyond 400 μW the characteristic begins to saturate. Notice, however, that the saturation occurs at output power levels that are much lower than the total power level on the next lower characteristic (add change in power to bias power level). This indicates that the saturation exhibited by the low-power characteristic is different from the lifetime-related saturation. We believe this saturation actually reflects the band filling induced reduction in the gain lever mechanism. To test this hypothesis we can estimate when this form of saturation should occur in the present structure using Fig. 2. Using the figure a change in control region carrier density of 1×10^{18} cm^{-3} should cause band filling induced changes in the gain lever mechanism (i.e., the effective g_c' is reduced). Assuming a carrier lifetime of 2 ns and control region dimensions of 0.01 μm $\times$ 3 μm $\times$ 5 μm gives an input power necessary to initiate saturation of only 220 μW of absorbed krypton power. This is in good agreement with the saturation level observed in Fig. 3. Therefore, we believe the saturation apparent in each characteristic is caused by band filling, whereas the saturation with increasing bias current level is a lifetime-related saturation. The latter observation is important because it suggests that by employing more quantum wells in the control region, the band filling related saturation can be greatly reduced. Use of five quantum wells, for example, would move the saturation level to over 1 mW of absorbed input power.

In conclusion, we have demonstrated a new method of amplification based on an optical gain lever mechanism and have presented a theoretical model of the effect. The model explains the measured gain as well as two forms of gain saturation that are apparent in the devices measured. To create gain two approaches are possible: either increase the ratio g_c'/g_s' or the ratio τ_c/τ_s substantially beyond unity. Both mechanisms may, in fact, be operative in the current structure, but it seems likely that the former effect is dominant owing to the behavior of quantum well gain with excitation. To further improve the gain beyond the measured 6 dB level, methods that address reduction of the slave differential gain or increase of the control differential gain can be explored. Operation of the slave region at higher excitation levels or selective n-type doping[5] of only the slave region are some examples. To increase the saturation power the simplest approach may be to use more quantum wells. This would reduce band filling induced reduction of the control differential gain. There are also obvious improvements that can be made to the device to improve input coupling efficiency such as use of an antireflection coating on the contact layer. Finally, although our discussion has described this device in the context of an optical to optical amplifier, it should be clear that the same mechanism could be used to amplify a weak modulation current to a laser diode by arranging for the current to directly modulate the control region of the device.

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