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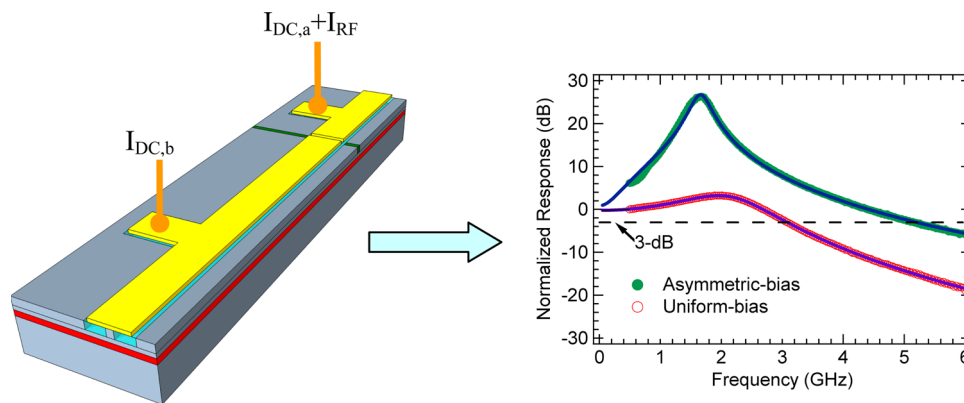
Y. Li, Member, IEEE
N. A. Naderi, Student Member, IEEE
V. Kovanis
L. F. Lester, Senior Member, IEEE

Enhancing the 3-dB Bandwidth via the Gain-Lever Effect in Quantum-Dot Lasers

Y. Li,[1] *Member, IEEE*, N. A. Naderi,[1] *Student Member, IEEE*, V. Kovanis,[2] and L. F. Lester,[1] *Senior Member, IEEE*

[1]Center for High Technology Materials (CHTM), University of New Mexico, Albuquerque, NM 87106 USA
[2]U.S. Air Force Research Laboratory, Sensors Directorate, OH 45433 USA

Abstract: We investigate the small-signal modulation response of two-section, gain-lever, quantum-dot semiconductor lasers. A three-pole modulation function is derived from a 3-D set of rate equations, and a 70% 3-dB bandwidth enhancement is computed and experimentally realized in an undoped quantum-dot gain-lever laser under extreme asymmetric-bias conditions. Finally, it is demonstrated that the 3-dB bandwidth is three times the free-running relaxation oscillation frequency in these types of laser structures, as opposed to 1.55 times in the case of conventional single-section lasers.

Index Terms: Gain lever, quantum dot, modulation bandwidth.

1. Introduction

The dynamic response of self-assembled quantum-dot (QD) semiconductor lasers has been studied extensively in recent years [1]–[3]. Part of the excitement surrounding these lasers is due to the promise they hold for high-speed applications in optical communications settings and microwave photonics applications, which is a consequence of their high differential gain and small chirp. As a result, considerable effort has been devoted to improving their high-speed characteristics, yet a small-signal modulation bandwidth of only about 11 GHz has been measured in standard injection devices [1]. Various device architectures have emerged recently that are appropriate candidates for improving the bandwidth of QD lasers, including tunnel injection [1], monolithically integrated optical feedback [4], strong optical injection that requires an optical isolator [5]–[7], and the monolithic optical gain lever [8]. This work identifies the unique optical characteristics of QDs that make them advantageous for the gain-lever device and describes the necessary equations for the future realization of high-bandwidth lasers using this approach.

The legacy gain-lever device work focused on modulation efficiency and enhancement for amplitude modulation (AM) and frequency modulation (FM). The first gain-lever device was proposed by Vahala *et al.* in 1989 in order to improve the efficiency of radio frequency (RF) to modulated light conversion [9]. They demonstrated a 6-dB enhancement in the AM modulation efficiency using an optical gain-lever quantum-well device. A 22-dB AM modulation increase was also realized by Moore and Lau using a 220-μm quantum-well device, with only a marginal increase in the intensity noise [10]. Since then, work has been conducted on not only AM characteristics but also on frequency modulation performance in inverted gain-lever optical circuits [11]. Recently, 8-dB and 20-dB modulation efficiency enhancements were demonstrated using p-doped and undoped QD lasers [8], [12]. Besides the modulation efficiency,
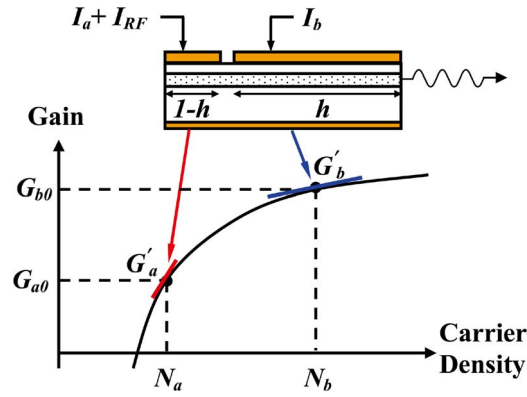
Fig. 1. Schematic view of the two-section gain-lever semiconductor laser with the evolution of modal gain with carrier density curve.

another important figure of merit for high-speed semiconductor lasers is the 3-dB modulation bandwidth. Broader bandwidth is very desirable in microwave/millimeter-wave photonics application. The bandwidth of a conventional directly modulated laser is limited by the intrinsic relaxation frequency of the laser itself [13]. As an alternative, an external modulator can provide larger bandwidth with high linearity and low chirp. However, it suffers from high cost and power consumption. In this paper, based on a newly derived, three-pole relative modulation response function [8], the 3-dB bandwidth enhancement of an optical gain-lever laser is examined theoretically under extreme asymmetric-bias conditions. A 1.7 bandwidth improvement is experimentally realized using a two-section QD laser. Our results also show for the first time that the 3-dB bandwidth of a gain-lever laser can be as much as three times its relaxation frequency, while the conventional value of this ratio is only 1.55 in a single-section laser. Theoretical results and experimentally recorded data are in full agreement.

2. Gain-Lever Effect

The gain-lever effect can be realized in a two-section device as depicted in Fig. 1 [10]. Using asymmetric current injection, the short section, which is referred to as the modulation section and labeled a, is DC-biased at a lower gain level than section b termed the gain section. This scheme provides a high differential gain under small-signal RF modulation. The longer gain section b is only DC-biased and supplies most of the amplification but at a relatively smaller differential gain. The fractional length of section b is denoted by h. Due to gain clamping at threshold and the nonlinear dependence of gain with carrier density, small changes in carrier density in the short section a produce a drastically larger variation in carrier density in section b to maintain the threshold gain condition. The outcome is that the modulation efficiency and the 3-dB bandwidth depend on the differential gain and damping rate ratios between the two sections.

The rate equations described in Ref. [10] for a two-section semiconductor laser are used to describe the dynamic behavior of the QD gain-lever lasers. The detailed carrier transport process in QD materials is neglected to simplify the problem [14]. Two separate differential equations are needed to describe the fluctuation of carrier density during current modulation. If we assume that the photon density is uniform in both the gain and modulation sections, then only one more rate equation is required for the photon density fluctuations. Consequently, the rate equations for the gain-lever optical circuit are given by

$$\frac{dN_a}{dt} = \frac{J_a}{ed} - \frac{N_a}{\tau_a} - G_a S \tag{1a}$$

$$\frac{dN_b}{dt} = \frac{J_b}{ed} - \frac{N_b}{\tau_b} - G_b S \tag{1b}$$

$$\frac{dS}{dt} = \Gamma[G_a(1-h) + G_b h]S - \frac{S}{\tau_p} \tag{1c}$$

where S is the photon density, and $J_{a,b}$, $N_{a,b}$, $\tau_{a,b}$, and $G_{a,b}$ are the injected current densities, carrier densities, carrier lifetimes, and unclamped material gains (the group velocity is included implicitly) in their respective sections. Γ is the optical confinement factor, τ_p is the photon lifetime, and d is the thickness of the active region. Using small-signal analysis, the following modulation response function is obtained:

$$\frac{s(\omega)}{j_a(\omega)} = \frac{\Gamma G'_{a0} S_0 (1-h)(i\omega + \gamma_b)/ed}{-i\omega^3 - (\gamma_a + \gamma_b)\omega^2 + iA_1\omega + A_2}. \tag{2}$$

The relative response function, which is normalized to zero frequency, is expressed as follows:

$$R(\omega) = \frac{s(\omega)/j_a(\omega)}{s(0)/j_a(0)} = \frac{A_2(i\omega/\gamma_b + 1)}{-i\omega^3 - (\gamma_a + \gamma_b)\omega^2 + i\omega A_1 + A_2} \tag{3}$$

in which A_1 and A_2 are

$$A_1 = \Gamma S_0 \left[G_{a0} G'_{a0}(1-h) + G_{b0} G'_{b0}h \right] + \gamma_a \gamma_b \tag{4a}$$
$$A_2 = \Gamma S_0 \left[G_{a0} G'_{a0}\gamma_b(1-h) + G_{b0} G'_{b0}\gamma_a h \right] \tag{4b}$$

and $G_{a0,b0}$ are the steady-state optical gains. γ_a and γ_b are defined as the damping rates in sections (a) and (b), respectively, and are given by

$$\gamma_a = \frac{1}{\tau_a} + G'_{a0} S_0 \tag{5a}$$

$$\gamma_b = \frac{1}{\tau_b} + G'_{b0} S_0 \tag{5b}$$

where $G'_{a0,b0}$ are the differential gains. The contribution from nonlinear gain is not included in these damping rate expressions at this moment but will be discussed below. The first term in the damping rate expression is inversely proportional to the spontaneous lifetime and the second term represents the inverse stimulated lifetime.

The A_2 expression consists of two products and each product consists of 4 individual terms. As mentioned above, the gain-lever device is always biased asymmetrically. The section b provides most of the gain but with a smaller differential gain. Therefore, the relationships $G_{b0} \gg G_{a0}$, $G'_{a0} \gg G'_{b0}$, and $\gamma_a \gg \gamma_b$ are valid. Considering that section b is much longer than section a, we can see that in the left-hand product of A_2, there are three small terms and one big term. However, in the right-hand product, there are three big terms and one small term. Therefore, the first product can be neglected and A_2 is approximated as

$$A_2 \approx \Gamma S_0 \left[G_{b0} G'_{b0}\gamma_a h \right]. \tag{6}$$

Under the steady-state condition, the rate equations give the relation between G_{a0}, G_{b0} and the threshold gain of the entire device (G_0) as

$$\Gamma[G_{a0}(1-h) + G_{b0}h] = \Gamma G_0 = G_{th} = \frac{1}{\tau_p}. \tag{7}$$

Using the same approximation described above, Eq. (7) can be approximated as

$$\Gamma G_{b0} h \approx \frac{1}{\tau_p}. \tag{8}$$

Considering that a high-photon-density case is desirable for a high-speed semiconductor laser, the device in our experiment is always running at relatively high power level. Thus, a high photon

density approximation can be made that allows the spontaneous damping term in γ_a and γ_b to be neglected

$$\gamma_a \approx G'_{a0}S_0 \tag{9a}$$

$$\gamma_b \approx G'_{b0}S_0. \tag{9b}$$

Substituting (9) and (8) into (6), we have

$$A_2 \approx \Gamma S_0 \left[G_{b0}G'_{b0}\gamma_a h \right] \approx \frac{\gamma_b \gamma_a}{\tau_p}. \tag{10}$$

Substituting Eq. (10) into (3), a new relative modulation response equation is derived

$$|R(f)|^2 = \frac{\left(\frac{\gamma_a \gamma_b}{8\pi^3 \tau_p}\right)^2 \left(1 + \left(\frac{2\pi f}{\gamma_b}\right)^2\right)}{\left[\frac{\gamma_a \gamma_b}{8\pi^3 \tau_p} - (\gamma_a + \gamma_b)\frac{f^2}{2\pi}\right]^2 + \left[\left[f_r^2 + \frac{\gamma_a \gamma_b}{4\pi^2}\right]f - f^3\right]^2} \tag{11}$$

where f_r is the resonance frequency defined by

$$f_r^2 = \frac{\Gamma S_0}{4\pi^2} \left[G_{a0}G'_{a0}(1-h) + G_{b0}G'_{b0}h \right]. \tag{12}$$

The relation $\omega = 2\pi f$ is used here.

In Eq. (11), the denominator has three poles instead of the usual two associated with a conventional single-section laser diode. Two damping rates are necessary to describe the different dynamics introduced by the asymmetric biasing of the device. It can be shown that the modulation-efficiency enhancement is proportional to the ratio of the differential gains of the two sections [8]. Thus, under the high-photon-density condition where $G'_{a0,b0}S_0 \gg 1/\tau_{a,b}$, this ratio can be expressed by the damping rates ratio according to Eqs. (5a) and (5b), which can be obtained by curve-fitting modulation response data using Eq. (11).

We now turn our attention to the limiting case in which $G_{a0} = 0$ and $h \approx 1$, which we call **extreme asymmetric bias**. Under this circumstance, the modulation section is biased close to its transparency level, and the gain section accounts for the majority of the device. The damping rate of the gain section γ_b and the relaxation frequency f_r are approximated according to the parameters of the uniform-bias device (for these particular parameters, the two-section laser can be viewed as a single-section laser), and then, we have

$$\gamma_b \approx K f_r^2 \tag{13}$$

in which the K-factor has its traditional meaning of damping rate over the relaxation frequency squared, which is standard for a single-section device [13]. Eq. (11) can then be recast as follows:

$$|R(f)|^2 = \frac{\left(\frac{gKf_r^4}{2\pi}\right)^2 \left(1 + \left(\frac{2\pi f}{Kf_r^2}\right)^2\right)}{\left[\frac{gKf_r^4}{2\pi} - \frac{(g+1)}{2\pi}Kf_r^2 f^2\right]^2 + \left[\left[f_r^2 + \frac{gK^2f_r^4}{4\pi^2}\right]f - f^3\right]^2} \tag{14}$$

where $g = \gamma_a/\gamma_b$. The f_r can be approximated under the extreme asymmetric bias condition as follows:

$$f_r^2 \approx \frac{G'_{b0}S_0}{4\pi^2 \tau_p}. \tag{15}$$

Since K and f_r are constants extracted from the response of the uniform-bias device, the modulation response function of the two-section laser is simplified as a function of g, which is the
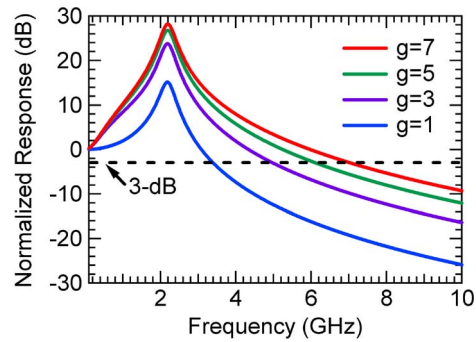
Fig. 2. Simulated modulation responses of a gain-lever QD laser operating in the extreme asymmetric-bias condition. As the damping rate ratio g becomes larger, the 3-dB bandwidth increases. The 3-dB bandwidth can be doubled when g equals 7.

damping rate ratio between the modulation and gain sections. In Fig. 2, the modulation response function is depicted based on Eq. (14) for $g = 1, 3, 5,$ and 7, where $g = 1$ is representing the uniform-bias condition. The relaxation frequency is set at 2.2 GHz and the K-factor at 0.5 ns, which are typical values for our QD devices. It is noted that f_r is relatively unchanged even under the extreme asymmetric bias as can be seen by examination of Eq. (15). Furthermore, as g increases, the response peak increases, and for $f > f_r$, the slope of the response curves are slightly flatter than that of the uniform-bias case. These two effects lead to higher 3-dB bandwidth in the asymmetric-bias case. When $g = 7$, the 3-dB bandwidth is almost twice that of the uniform-bias case. It is known that in single-section lasers, when the damping rate $\gamma \ll 2\pi f_r$, the ratio between f_{3dB} and f_r has a constant value of 1.55 [13]. In Fig. 2, f_r is relatively unchanged as g increases, so that values for f_{3dB}/f_r equaling 2.2, 2.8, and 3.2 when $g = 3, 5,$ and 7, are calculated, respectively. This is one of the unique modulation characteristics for two-section lasers and has been reported before in a two-section DFB laser [15]. It is worth noting that since the nonlinear gain effect scales with photon density in each section independent of the bias arrangement, the γ_a and γ_b are dissimilar primarily because of the difference in differential gains but not from the nonlinear gain.

3. Modulation Bandwidth Enhancement in the QD Gain-Lever Device

The undoped QD diode laser material employed in our measurements contains a 10-stack InAs/InGaAs "dots-in-a-well" (DWELL) active region that emits around 1.23 μm [16]. The laser structure was grown by molecular beam epitaxy (MBE) on a (001) GaAs substrate. The multisection device was fabricated by standard processing techniques. A ridge waveguide of 3.5 μm was formed by contact lithography and inductively coupled plasma (ICP) etching. A reconfigurable, segmented-contact layout was used to define the anodes of the laser [17]. This unit cell approach for building the gain-lever device allowed us greater flexibility in examining different configurations. The length of each cell was 0.25 mm, and they were electrically isolated from each other by proton implantation across a 10-μm gap. The optical waveguide is common to all sections. Another benefit of this multisection layout is that the gain spectra can be measured through the segmented-contact method [18], [19], and then, the two-section gain-lever laser can be constructed from the same device by rearranging the wire-bonding.

As described in the previous section, the gain-lever effect is based on the **sublinear relationship** between gain and current density (G–J); therefore, an accurate model of this dependence is highly desirable. In this paper, a highly accurate segmented-contact method is used to measure the gain spectra, the details of which are described elsewhere [18], [19]. Fig. 3(a) shows the net modal gain spectra at a temperature of 20 °C of the QD active region. It can be seen that this material shows a unique camel-back gain characteristic under saturation at current densities higher than 18 mA/section (equivalent to 1200 A/cm^2). In other words, the difference in the maximum gain between the ground state and excited states is very small. This is particularly advantageous for
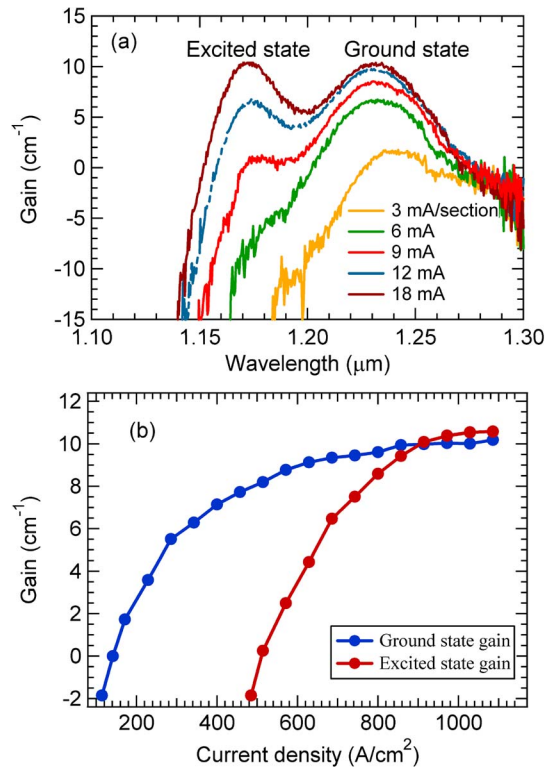
Fig. 3. (a) Net modal gain spectra of a 10-stack undoped QD device. (b) Dependence of the net modal gain on injected current density in the QD device at 20 °C.

inhibiting excited state lasing in the gain-lever device. Fig. 3(b) shows the gain versus current density curves of the ground and excited states by tracking the gain at a lasing wavelength of 1236 nm and 1172 nm, respectively. Both curves saturate at approximately 10.5 cm^{-1}.

The two-section gain-lever laser is formed from the multisection device by wire-bonding the segmented contact cells together. The total cavity length of the gain-lever device is 1.25 mm. The gain section, which is 1 mm long, contains four 0.25-mm-long cells. The modulation section is 0.25 mm long, yielding a value of $h = 0.8$. For the high-speed experimental setup, two precision current sources are used to provide the current flow into each section. DC and small-signal microwave signals are applied to section (a) from port 1 of an HP8722D vector network analyzer. Section b is solely DC biased. The output of the laser diode was coupled into a tapered fiber and then collected by a New Focus high-speed photodetector that was connected to port 2 of the HP8722D.

The static light-current (LI) characteristics of the gain-lever laser are plotted in Fig. 4. Under uniform bias, the threshold current is 17 mA at 20 °C and the center emission wavelength is 1.235 μm when the bias current is 40 mA. In Fig. 5(a) and (b), the experimentally measured modulation responses of the QD gain-lever laser are plotted for the uniform and asymmetric-bias conditions at a constant power level of 6.5 mW/facet and 7.9 mW/facet, respectively. The K-factors under uniform-bias condition are 0.51 ns and 0.52 ns for these two cases. The bias current densities applied to modulation sections are 91 A/cm^2 and 115 A/cm^2, respectively, which are slightly lower than the transparency current density. The bias applied to the gain section b is over 1200 A/cm^2 to realize saturation at the ground state wavelength. The damping dates γ_a and γ_b can be obtained by curve-fitting the experimental data using Eq. (11). In Fig. 5(a), f_r, γ_a, and γ_b are fitted as 1.82, 8.48, and 2.95 GHz, which is close to the $g = 3$ condition. Since the value of h is 0.8 in the real device instead of 1 as in our simulation, the relaxation frequency of the asymmetric-bias gain-lever laser is somewhat smaller than that of the uniform-bias device as shown in Fig. 5. The ratio of the 3-dB bandwidth of the asymmetric to uniform-bias case can be read as 1.3. This is also consistent with the
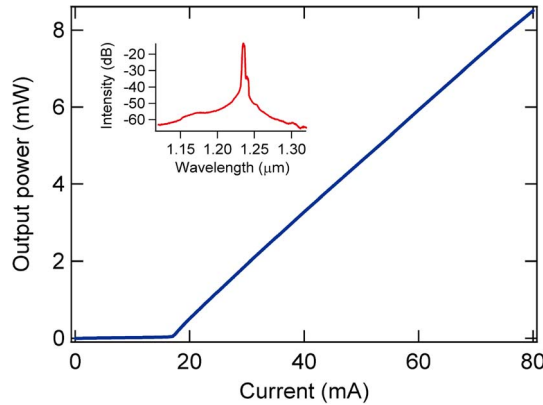
Fig. 4. L-I curve of the gain-lever laser under the uniform-bias condition at 20 °C. The inset is the lasing spectrum when the total bias current is 40 mA.
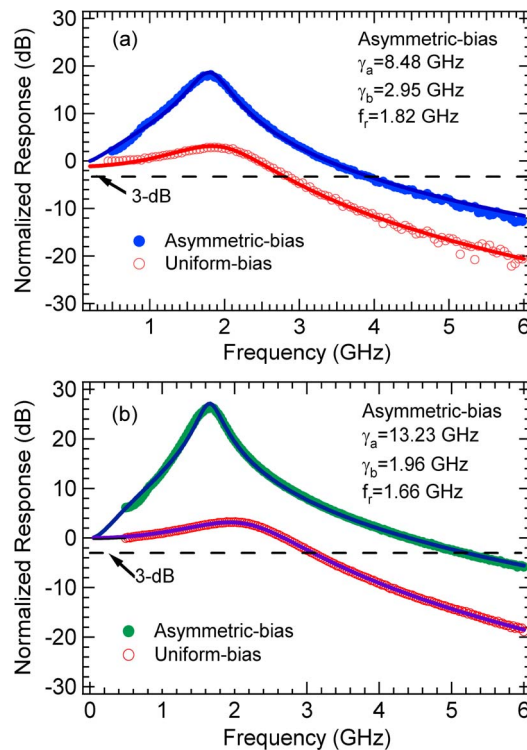

Fig. 5. Experimental modulation responses of a gain-lever laser for asymmetric and uniform-bias conditions. (a) At a power level of 6.5 mW/facet, the 3-dB bandwidth ratio of the asymmetric to uniform-bias condition is 1.3. (b) At a power level of 7.9 mW/facet, the 3-dB bandwidth ratio of the asymmetric to uniform-bias condition is 1.7.

theoretical curve of $g = 3$ in Fig. 2. In Fig. 5(b), f_r, γ_a, and γ_b are fitted as 1.66, 13.23, and 1.96 GHz. The damping rate ratio is approximately 7, and the measured 3-dB bandwidth ratio is 1.7, which is close to the theoretical $g = 7$ case shown in Fig. 2 in which $f_{3dB}/f_{3dB\_uni} = 2$. In Fig. 5(b), the 3-dB bandwidth of the asymmetric-bias case is about 5.1 GHz, which is about 3X higher than the relaxation frequency of 1.66 GHz. This is the first time such an enhancement has been reported. Therefore, it is confirmed that QD gain-lever devices can demonstrate bandwidth enhancement

under particular pumping conditions and that, for all intents and purposes, the laser described here is a good example of the extreme asymmetric-bias case.

The 3-dB bandwidth improvement, however, does come at the expense of modulation efficiency, which is proportional to $(1 - h)$ under extreme asymmetric bias. Compared with the uniformly modulated case, the efficiency was observed to drop by 7 dB, which is consistent with $(1 - h) = 0.2$. It is also worthwhile to discuss the limits to f_{3dB} using extreme asymmetric biased gain-lever devices. As g gets very large, Eq. (12) shows that f_r trends to zero, since one section has nearly zero optical gain and the other has nearly zero differential gain. Thus if g is increased too much, the bandwidth enhancement is eliminated entirely. Consequently, we restricted the device's operating regime such that f_r was not significantly below that of the uniformly biased case. If a precise mathematical model describing the relationship between gain and carrier density is established, it is possible to find the limit on the maximum achievable bandwidth and the optimum g value.

4. Conclusion

In summary, a new relative small-signal modulation response function was derived to describe the RF characteristics of a two-section gain-lever QD laser. Based on this function, it has been shown that under an extreme asymmetric-bias condition, a laser employing the gain lever should demonstrate an enhanced 3-dB bandwidth compared with a regular single-section laser. A 1.25-mm-cavity-length gain-lever laser was fabricated from a 10-layer QD active region. The relationship between gain and current density of this material was measured by the segmented-contact method, and the unique gain saturation characteristics of QD optical media were shown. The gain-lever device demonstrated up to a 2X 3-dB bandwidth enhancement, which was consistent with theoretical predictions. The new relationship between 3-dB bandwidth and relaxation frequency was explored in the gain-lever laser as well. The value of $f_{3dB}/f_r = 3$ was shown in the gain-lever laser instead of the typical value of $f_{3dB}/f_r = 1.55$ for a single-section cavity. Even though the operating condition for bandwidth enhancement is very strict and a larger signal distortion may occur due to increased nonlinearities [20], [21], the gain-lever laser provides an alternative and monolithic way to improve modulation performance of semiconductor lasers without changes in the laser structure and fabrication. Larger bandwidth enhancements under relaxed conditions are expected by improving the maximum gain in QD materials. Such improvements should be compared and contrasted with the bandwidth-enhancing characteristics of strongly optically injected diode lasers [5], [6] that provide large bandwidth improvements, with suppressed nonlinear behavior, but at the expense of a more complicated system.

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