Multi-section gain-lever quantum dot lasers

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ABSTRACT

The modulation characteristics of multi-section gain lever quantum dot lasers are investigated in this paper. A 20-dB enhancement in the amplitude modulation efficiency is observed in a two-section quantum dot laser. Based on rate equation analysis a novel modulation response equation is derived to describe the device dynamics. In addition the dependence of the modulation efficiency enhancement and 3-dB bandwidth on the length of the modulation section is discussed. A conservative estimate of the gain lever value of 33 is derived from the measured results.

Keywords: quantum dots, semiconductor lasers

1. INTRODUCTION

Self-assembled quantum dot (QD) lasers have been studied extensively in recent years.[1-4] Due to the delta-like density of states of QDs, lasers fabricated from these novel materials provide many superior characteristics such as ultralow threshold current,[3] small linewidth enhancement factor, and low temperature dependence of the threshold current.[4] QD lasers are a strong candidates for high-speed modulation due to their high differential gain and direct modulation with small chirp. Substantial effort has been made to improve the modulation characteristics of quantum dot lasers.[5] One possible method for realizing this improvement is through the technique of the optical gain lever.

The gain-lever effect has been studied previously to improve the modulation efficiency of both intensity modulation and frequency modulation of semiconductor lasers. The gain lever device usually consists of two electrically-isolated but optically-coupled sections in which the modulation section, is DC biased at a low gain level with high differential gain and RF-modulated. The other, the gain section, is only DC-biased at a high gain level with low differential gain. Due to gain clamping and the sub-linear relationship between gain and carrier density in low dimensional media such as quantum wells (QW), any small change in injection current in the modulation section will lead to larger changes in the gain section. 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. Most previous research has been done on QW gain lever lasers, while quantum dot (QD) emitters are expected to demonstrate more significant gain lever action due to their stronger gain saturation with carrier density.[6,7] Recently, an 8-dB enhancement in the intensity modulation efficiency was reported by our group.[8]

In this paper, the modulation efficiency and the 3-dB bandwidth in gain lever quantum dot lasers constructed from a multi-section process are examined. One of the benefits of the multi-section layout is that the ratio of the modulation and gain section lengths can be varied without switching to another device. A 20-dB modulation efficiency enhancement in an un-doped QD two-section gain lever laser diode is presented. The dependence of modulation efficiency improvement and 3-dB bandwidth on the length of the modulation section is also investigated. Realistic estimates of the gain lever are calculated from the measured data and new theoretical equations describing the device's modulation response.

2. GAIN LEVER EFFECT

The gain lever effect is based on the sub-linear relationship between the optical gain and carrier density (approximated here by gain vs. injected current density) and is realized in the two-section device shown in Fig. 1. The parameter h is the fractional length of the gain section. Using asymmetric electrical current pumping, the short modulation section, which is labeled a, is DC biased at a lower gain level that provides high differential gain under small-signal RF modulation. The longer gain section b is only DC biased and supplies most of the gain, but at a relatively smaller differential gain. Due to

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gain clamping at threshold and the non-linear dependence of gain with carrier density, small changes in carrier density in section *a* produce a much larger variation in gain and carrier density in section *b*. It was previously found in QW lasers that the modulation efficiency enhancement is proportional to the ratio of the differential gain in the two sections provided that the photon density is low or the damping rates in each section are roughly equal.[6]

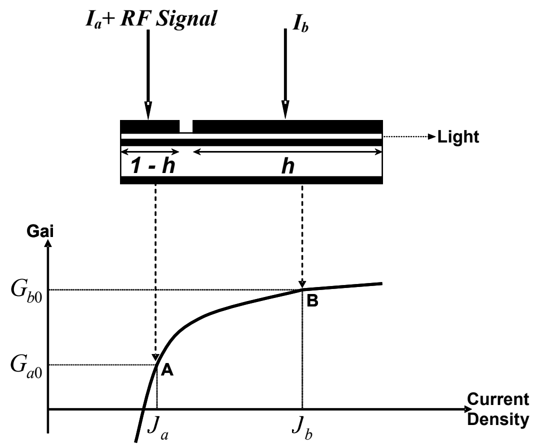

Fig. 1 Configuration of the two-section QD laser

The rate equations for the two-section laser can be expressed as[6]

$$
\begin{aligned}
\frac{dP}{dt} &= P\left[\Gamma G_a(1-h)+\Gamma G_b h-\frac{1}{\tau_p}\right]\\
\frac{dN_a}{dt} &= \frac{J_a}{ed}-\frac{N_a}{\tau_a}-G_a P\\
\frac{dN_b}{dt} &= \frac{J_b}{ed}-\frac{N_b}{\tau_b}-G_b P
\end{aligned}
\qquad (1)
$$

Where P is the photon density, $J_{a,b}$, $N_{a,b}$, $\tau_{a,b}$ and $G_{a,b}$ are the current density, carrier density, carrier lifetime and unclamped gains in the respective sections, Γ is the optical confinement factor, and h is the fractional length of the gain section. For the quantum dot laser media, a new relative modulation response equation is found by performing small signal analysis on the rate equations and assuming that the spontaneous carrier lifetime is much larger than the stimulated lifetime:[8]

$$
|R(f)|^2 \propto \frac{\left(\dfrac{\gamma_a\gamma_b}{2\pi\gamma_{uni}}\right)^2\left(1+\left(\dfrac{2\pi f}{\gamma_b}\right)^2\right)}{\left[\dfrac{\gamma_a\gamma_b}{2\pi\gamma_{uni}}-(\gamma_a+\gamma_b)\dfrac{f^2}{2\pi}\right]^2+\left[\left[f_r^2+\dfrac{\gamma_a\gamma_b}{4\pi^2}\right]f-f^3\right]^2} \qquad (2)
$$

Where f_r is the resonance frequency, γ_{uni} is the damping factor when the two sections are pumped uniformly (in this case, the two section laser can be viewed as a single section laser). It can be seen that the denominator of this response equation has three poles instead of the two of a typical single-section diode laser. The two damping rates included in (2) are related to the carrier lifetime, photon density and differential gain in each section as follows:

$$\gamma_a = \frac{1}{\tau_a} + G'_{a0}P, \qquad (3a)$$

$$\gamma_b = \frac{1}{\tau_b} + G'_{b0}P, \qquad (3b)$$

Where $G'_{a0,\,b0}$ are differential gains in sections *a*, *b* respectively. When the device is operated at relatively high power level, that is the case in this work, the contribution of the inverse carrier lifetime to the damping rate is small and this condition is reflected in (2). In this instance, the gain lever factor can be simplified as follows:[8]

$$lever = \frac{G'_{a0}}{G'_{b0}} = \frac{\gamma_a}{\gamma_b}, \qquad (4)$$

3. GAIN MEASUREMENTS

As noted in the section above, the gain lever effect is based on the sublinear relationship between gain and current density, *G(J)*, so an accurate model of this dependence is highly desirable. There are several methods to measure the gain as a function of current density in semiconductor lasers). Hakki and Paoli first determined the gain from the depth of modulation [9], i.e., the peak-to-valley ratio, in the amplified spontaneous emission (ASE) caused by the Fabry–Perot resonances of the laser cavity. For an appropriate evaluation of the gain, the Hakki-Paoli method requires a high wavelength resolution of the measurement system, and it is only accurate below the laser threshold. An alternative approach consists using the fact that modal gain is equal to the sum of internal loss and mirror loss at threshold in a laser. Thus, the *G(J)* relationship can be obtained by measuring the threshold gain of lasers with different cavity length. However, since this involves cleaving and preparing many devices, it is not easy to get an arbitrary point on the *G-J* curve. In this paper, we use an improved segmented contact method to measure the gain spectra. This technique does not require high spectral resolution, is compatible with optical fiber butt coupling, and can extract the gain over a wide range of conditions.[10] Figure 2 and 3 show the net modal gain data for a 10-stack undoped QD laser media which is used for the gain lever device. It can be seen from Fig. 2 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. Figure 3 show the *G(J)* 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}.

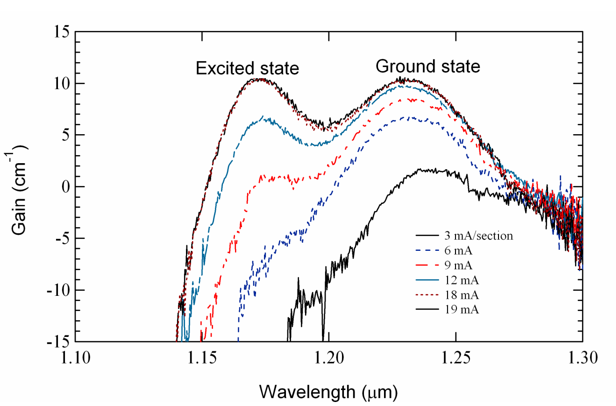

Fig. 2. Net modal gain spectra of a 10-stack undoped QD device

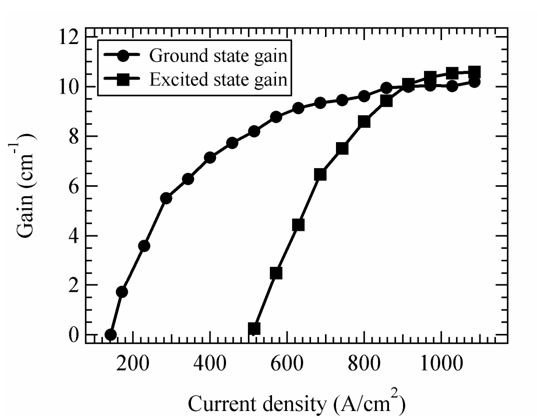

Fig. 3 Dependence of the net modal gain on injected current density in the QD device.

4. DEVICE FABRICATION

The multi-section devices used in the following set of measurements contain a 10-stack InAs/InGaAs DWELL active region that emits around 1.23 µm. The laser structure was grown by molecular beam epitaxy (MBE) on a (001) GaAs substrate. 3-µm wide single-mode ridge waveguides were fabricated by standard processing techniques. First, the sample was dry-etched to form 3-µm wide ridges using a BCl_3 inductively-coupled plasma. Then standard BCB processing was applied for planarization and to isolate the p-type metal and the etched upper cladding layer. A segmented-contact mask was used to define the p-type metal contact and ion implant isolation. The electrical isolation between each section was performed by proton implantation. The length of each isolated section is 0.25-mm. After lapping and polishing of the substrate, Au/Ge/Ni/Au n-type metallization was deposited, and the sample was annealed at 380°C for 1 minute. The processing procedure is shown in Fig. 4.

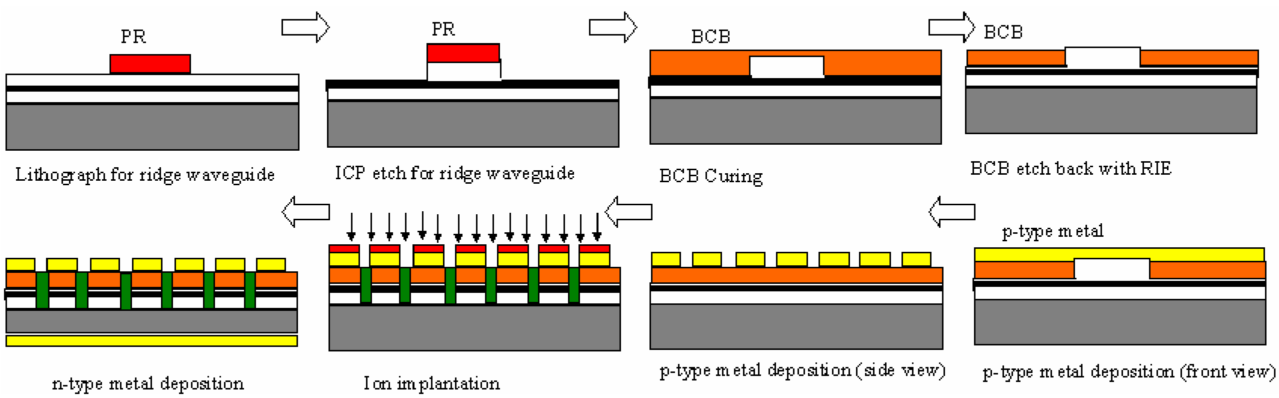

Fig. 4. Multi-section device processing flow chart.

4. MODULATION CHARACTERISTICS

The two devices used in this work are 1.25-mm (device #1) and 1.5-mm (device #2) long, and included 5 and 6 electrically-isolated sections, respectively. The benefit of the multi-section layout is that one can vary the ratio of the modulation and gain section lengths without switching to another device. For example, we can use one device to perform the modulation measurement as if we had access to three devices with h = 0.83, 0.67, 0.5, respectively (corresponding to modulation section lengths of 0.25-mm, 0.5-mm and 0.75-mm for the 1.5-mm cavity device). The high-speed modulation experimental setup is shown in Fig. 5. The RF modulation signal is provided by an HP 8722 network analyzer (port 1). The output light from the two-section laser is collected by a lensed single-mode fiber connected to a high-speed photodetector; the modulation response signal is transmitted into port 2 of the network analyzer.

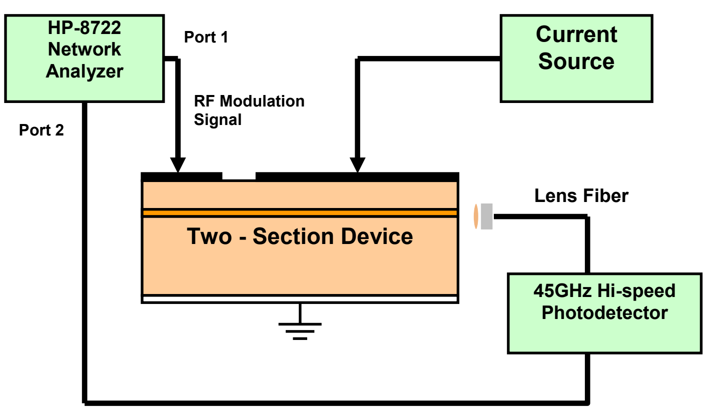

Fig. 5. RF modulation response measurement setup.

The modulation efficiency enhancement was measured by comparing the responses for uniformly and asymmetrically pumped cases. In the asymmetric configuration, the current injection into the modulation section is decreased, while the current into the gain section is increased to maintain an output power equal to the uniformly pumped condition. The fractional length $h = 0.8$. In Fig. 6, modulation responses for the uniform and asymmetric cases at a constant power level of 4 mW/facet are plotted. From the solid curve in the figure, a 20-dB modulation efficiency enhancement is obtained for device #1 when the shorter section is biased just below transparency. It is noted that as the injected current in the shorter section decreases, the modulation efficiency enhancement rises due to the increasing gain lever.

A conservative estimate of the gain lever, γ_a/γ_b, can be made under certain assumptions. For the case of large gain levers, $\gamma_a >> \gamma_b$, and the frequency f near zero, the modulation response function given in eqn. (2) approaches $|R(f)|^2 = (\gamma_a/\gamma_{uni})^2$. Thus, the 20-dB enhancement corresponds to $\gamma_a/\gamma_{unit} = 10$. The damping rate of the uniformly pumped laser is found to be 8.2 GHz from the data presented in Fig. 6 (solid curve) so that γ_a is 82 GHz for the asymmetric pumping. We separately determined an inverse carrier lifetime of 2.5 GHz, which is the lower limit to γ_b, from a plot of the damping rate vs. the square of the relaxation frequency. Consequently a gain lever value of 33 is calculated, which is approximately 3 times greater than that previously reported in QW gain lever laser diodes.

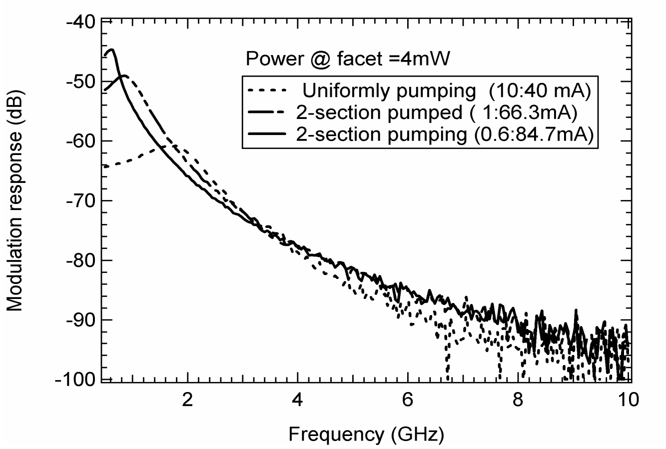

Fig. 6. The modulation response for the uniform and 2-section (asymmetrically pumped) cases.

Figure 7 shows the modulation efficiency enhancement as a function of the normalized gain, G_{a0}/G_0, in the modulation section for different fractional lengths h in device #2. The DC bias current must be changed as the modulation section getting longer in order to keep the same current density applied on the section. As h decreases, it can be seen that the modulation efficiency enhancement increases for a given normalized gain in the modulation section. The reason for this behavior is that the shrinking gain section must compensate for the larger gain deficit, which in turn enhances the asymmetry between the 2-sections. Since the current density in the modulation section stays roughly constant at a given normalized gain, the gain section must be biased at a higher current density to maintain the same output power . From the G-J curve obtained in Fig. 3, the differential gain of section “b” (G_{b0}') is smaller when the current density is high. Therefore, the modulation efficiency enhancement gets larger according Eqn. (4). Similarly, for a fixed h value, when the pump level in section “a” is increased (higher normalized gain), the differential gain becomes smaller, so the modulation efficiency enhancement decreases as normalized gain increases. We should notice here that the current density of the modulation section cannot be reduced too much. Otherwise, the bias current of the gain section must be very high to keep the same output power, which may cause an undesirable mode hop into the excited state transition of the quantum dot.

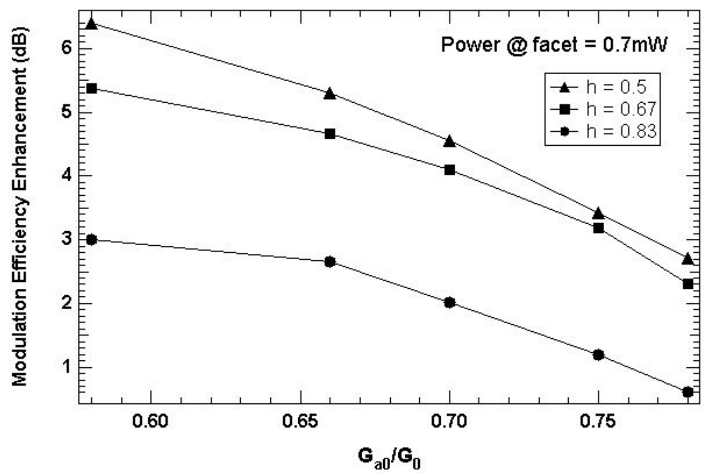

Figure 7. The function of modulation efficiency enhancement depends on normalized gain G_{a0}/G_0 for different *h* value.

The variation of the 3-dB bandwidth with normalized gain for different *h* in device #2 is plotted in Fig. 8. For the same value of *h*, it shows that the modulation bandwidth decreases with more asymmetric pumping. The 3-dB bandwidth also becomes heavily *h* dependent with increased asymmetry in the two-section pumping (lower G_{a0}). This may be due to the nonlinear gain suppression taking effect when the gain section must be pumped harder for the smaller *h* case.

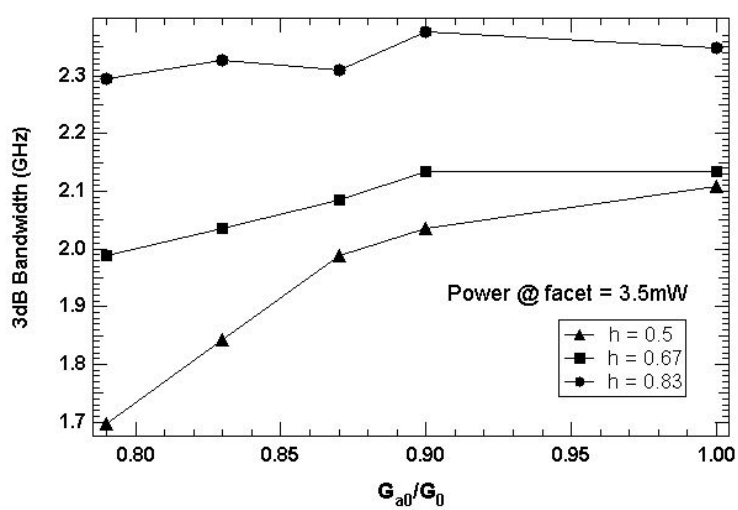

Figure 8. The dependence of 3-dB bandwidth on normalized gain for different *h* value.

5. Conclusion

The modulation response characteristic of gain lever quantum dot lasers was studied in a multi-section configuration. Using the improved segment contact technique, the gain spectra and G-J curve were obtained from multi-section devices. A 20-dB modulation efficiency enhancement was observed in a 1.25-mm two-section gain laser corresponding to a large gain lever of 33. Without switching to other devices, the dependence of the modulation efficiency enhancement and 3-dB bandwidth on fractional length *h* of the gain section was investigated. In the range of this measurement, as *h* decreases, the modulation efficiency enhancement increases, while 3-dB bandwidth becomes smaller.

REFERENCES

1. D. Bimberg, N. Kirstaedter, N. N. Ledentsov, Zh. I. Alferov, P. S. Kop'ev, and V. M. Ustinov, "InGaAs-GaAs Quantum-Dot Lasers", *IEEE J. of Select. Top. Quantum Electron*, vol. 3, pp. 196-205, 1997.
2. L. F. Lester, A. Stintz, H. Li, T. C. Newell, E. A. Pease, B. A. Fuchs, and K. J. Malloy, "Optical Characteristics of 1.24 μm InAs Quantum-Dot Laser Diodes", *IEEE Photon. Technol. Lett*., vol .11, pp. 931-933, 1999.
3. G. T. Liu, A. Stintz, H. Li, T. C. Newell, A. L. Gray, P. M. Varangis, K. J. Malloy, and L. F. Lester, "The Influence of Quantum-Well Composition on the Performance of Quantum Dot Lasers Using InAs/InGaAs Dots-in-a-Well (DWELL) Structures", *IEEE J. of Quantum Electron,* vol. 36, pp. 1272-1279, 2000.
4. H. Chen, Z. Zou, O. B. Shchekin, and D.G. Deppe, "InAs quantum-dot lasers operating near 1.3μm with high characteristic temperature for continuous-wave operation", *Electron. Lett*, vol. 36, pp. 1703-1704, 2000.
5. S. Fathpour, Z Mi and P. Bhattacharya, "High speed quantum dot lasers", *J. Phys. D: Appl. Phys*. vol. 38, pp. 2103-2111, 2005.
6. N. Moore and K. Y. Lau, "Ultrahigh efficiency microwave signal transmission using tandem-contact single quantum well lasers", *Appl. Phys. Lett*., Vol. 55, pp. 936-938, 1989.
7. C. P. Seltzer, L. D. Westbrook, and H. J. Wickes, "The "Gain-lever" effect in InGaAsP/InP Multiple Quantum Well Lasers", J. Light. Techno., Vol. 13, pp. 283-289, 1995.
8. N. A. Naderi, Y, Li and L. F. Lester, " Quantum dot gain lever laser diode" , presented at *IEEE LEOS Annual. Mtg.*, Montreal Canada , 2006.
9. B.W. Hakki and T. L. Paoli, "Gain spectra in GaAs double-Heterostructure injection lasers," *J. Appl. Phys.*, vol. 46, pp. 1299–1305, 1975.
10. Y.-C. Xin, H. Su and L. F. Lester, "Determination of optical gain and absorption of quantum dots with an improved segmented contact method", *SPIE Photonics West Annual. Mtg,*. San Jose, CA, 2005