

Gain Characteristics of 1.55- μm High-Speed Multiple-Quantum-Well Lasers

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Abstract—We describe the important characteristics of high-speed p-doped compressively strained MQW lasers obtained from comprehensive below-threshold dc measurements. Results of gain and differential gain versus wavelength and carrier density are verified by above-threshold resonance measurements. Measurement-derived design curves of gain, differential gain, and linewidth enhancement factor allow device optimization for high speed and low chirp.

LONG-WAVELENGTH semiconductor lasers have achieved modulation bandwidths of 25 GHz for both Fabry-Perot and DFB structures [1], [2]. The intrinsic response is set mainly by the differential gain above threshold, and much effort has been put into increasing this value. In order to improve the performance to higher bandwidths it is necessary to fully understand this and other material parameters of the device. The level of wavelength chirping of single-mode (DFB) lasers is also directly related to the differential gain, with higher values producing lower chirp. For this reason optimization for high speed and low chirp both require very high differential gain. The differential gain can be determined from high-speed measurements of relative intensity noise [3], or using modulation techniques [4], [5]. This approach, however, requires a large amount of data to produce a single value of differential gain from one device. This value is applicable to the operating point (threshold value) of that device. Taking data on a number of devices using different parameters such as cavity length or mirror reflectivity to change the operating point will provide more understanding of device operation. However, variations in devices, for example from active-region width fluctuations, tend to obscure the trends.

In this letter we show that extensive, careful measurements of the dc characteristics of a small number of devices, once verified by high-speed measurements, can give a far better understanding of device operation and allow for optimization of the structure. We take 1.5- μm Fabry-Perot lasers [1] with p-doped compressively strained active regions that have achieved a modulation bandwidth of 25 GHz, and from dc measurements characterize the gain, differential gain, and material linewidth enhancement factor “ α ” versus carrier density and wavelength. The accuracy of the differential gain measurements are verified by high-speed measurements. The results show the very high value of differential gain seen in

these devices, which explains the high measured bandwidth, and also the intrinsic bandwidth at actual operating conditions of around 40 GHz.

Sub-threshold gain measurements are carried out over a wide range of wavelengths and applied currents. The TE polarized spontaneous emission spectrum is measured from one of the two uncoated facets of the device. The modulation of the spontaneous emission spectrum provides values of gain using the Hakki and Paoli method [6], together with the Cassidy modification [7] at higher values of gain. The device described in this paper has a length of 250 μm , shorter than the fastest devices in [1], but providing better contrast in the Fabry-Perot spectrum due to the larger mode spacing. Examples of measured spontaneous and gain spectra are shown in Fig. 1. These results are extremely clean over a wide range of wavelength (1520 to 1700 nm), net modal gain (0 to -160 cm^{-1}), and drive current (0.5 to 11.5 mA), up to the device threshold at 11.5 mA, where the net modal gain equals zero. Clean gain spectra are necessary in order to calculate the derivative (dG/dN). The internal loss is measured using the Andrekson technique [8], giving a value of 50 cm^{-1} at threshold.

With all measurements using bias current as an independent parameter, it is necessary to relate this current to the carrier density in the active region. This relationship can be found from measurements of the carrier lifetime [9]. The carrier lifetime was found from the small signal modulation response of the device, which was fitted to a simple single-pole response over the frequency range of 1 MHz to 1 GHz. Excellent fits were found over this range due to the small parasitic components of this high-speed device. The lifetimes were modified to take account of the device impedance [10]. The carrier density is calculated from the integral

$$N = \int_0^{I_1} \frac{\eta_i(I)\tau(I) dI}{eV} \quad (1)$$

where N is the carrier density, I the applied current, $\tau(I)$ the carrier lifetime, e the electronic charge, and V the active volume. This equation includes the non-unity internal efficiency of the laser $\eta_i(I)$. The internal efficiency is determined from the slope of the light/current characteristics (as the internal loss and mirror loss are known), with the linear variation of efficiency from the curves being extended down to zero current. The measured carrier lifetimes and calculated carrier density curves are shown in Fig. 2. The device has a threshold carrier density of $1.6 \times 10^{18} \text{ cm}^{-3}$, and a transparency carrier

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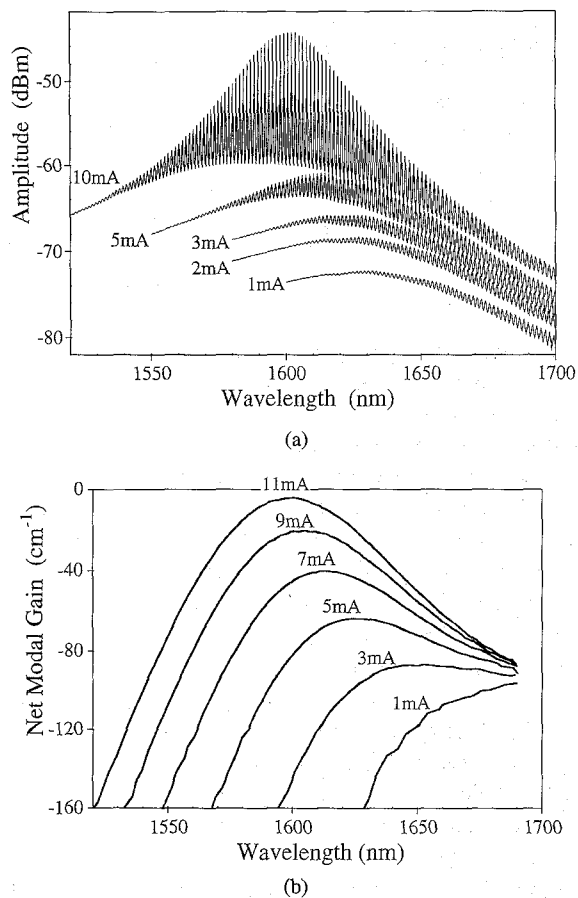


Fig. 1. (a) TE polarized spontaneous emission spectra and (b) calculated TE gain spectra at various bias currents.

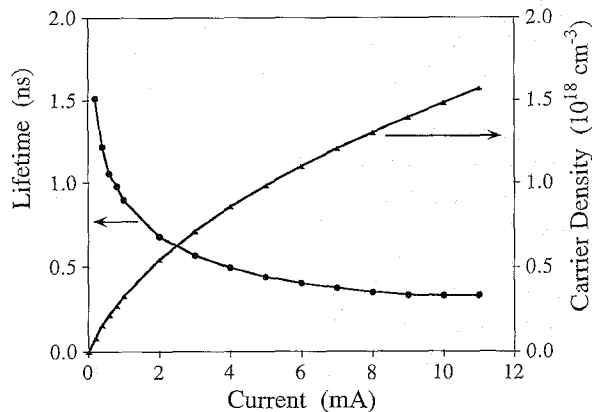


Fig. 2. Carrier lifetime and carrier density versus bias current.

density of $1.0 \times 10^{18} \text{ cm}^{-3}$. These values are low for a quantum-well laser, due mainly to very high differential gain.

The gain curves can be combined with the carrier density data to give gain as a function of carrier density and also the differential gain dG/dN . Fig. 3(a) shows the values of differential gain versus wavelength at various bias currents. The threshold value of $11.5 \times 10^{-20} \text{ m}^2$ is obtained by finding the value at the threshold current and lasing wavelength of 1600 nm. This value is four times larger than seen in typical bulk active lasers, and higher than measured from undoped MQW lasers. Even higher values could be obtained

if threshold were achieved at a lower current, and particularly if the lasing wavelength could be detuned away from the gain peak, as in a DFB laser. A DFB laser with a large negative detuning of the wavelength could produce almost double this value of differential gain. For comparison, the differential gain is also calculated from resonance frequency versus $(\text{output power})^{0.5}$ curves, found from high-frequency measurements [6]. The agreement between the two values is good, with the dynamic measurement giving a value of $13.7 \times 10^{-20} \text{ m}^2$. This agreement verifies the static measurements, giving confidence that the measured curves can be used to optimize device performance. To further show the predictive power of these measured curves, the device used in the first measurements was modified by adding high-reflectivity (HR) coatings, with $R \sim 95\%$. The change in net modal gain at threshold compared to the uncoated value is easily calculated from the change in mirror loss. The measurements predict threshold currents of approximately 9 mA and 7 mA after one and two HR coatings respectively, together with lasing wavelengths of 1605 and 1615 nm [see Fig. 3(b)]. These predictions agree extremely well with the measured threshold currents and new lasing wavelengths after coating. The predicted differential gains are 14.5 and $15 \times 10^{-20} \text{ m}^2$. High-speed resonance measurements were carried out after each coating. Curves showing resonance frequency versus $(\text{output power})^{0.5}$ were made, and excellent straight line fits found, giving values of 6.85, 9.0, and 52.3 GHz/mW^{0.5} for the slopes, which give values for the differential gain of $13.7 \times 10^{-20} \text{ m}^2$ (uncoated) and $16.5 \times 10^{-20} \text{ m}^2$ (1 HR coating). The value for two HR coatings is not accurate due to the large uncertainty of the mirror loss. In this case a value can be found using curves of resonance frequency versus $(I - I_{th})^{0.5}$ and fitting a straight line at the lower bias levels (before carrier leakage or heating affects the output power). This gives slopes of 2.22, 2.45, and 2.55 GHz/mA^{0.5}, which convert to values for differential gain of 12.2, 14.9, and $16.1 \times 10^{-20} \text{ m}^2$ for uncoated, one, and two HR coatings, respectively [see inset to Fig. 3(b)]. The value of differential gain from static measurements and high-frequency resonance measurements give good agreement for all cases of facet reflectivity, showing that the measured curves offer a good way to understand and then optimize device performance.

In a single-mode laser such as a DFB, wavelength chirping under direct modulation has a direct impact on the system performance. The linewidth enhancement factor " α " is directly related to the amount of chirp, with a low value giving the lowest chirp and best performance. It is defined as

$$\alpha = -2k_o \frac{dn/dN}{dG/dN} \quad (2)$$

where n is the active region index and k_o is the propagation constant. The dn/dN term can be approximated in a simple way from the optical spectra to allow " α " to be calculated. The wavelength of individual Fabry-Perot modes in the sub-threshold spontaneous emission spectra vary with bias, and this variation can be tracked versus carrier density giving $\delta\lambda/\lambda_o$, which equals $\delta n_{\text{eff}}/n_{\text{eff}}$. The value δn_{eff} is approximately equal to $\Gamma\delta n$, the confinement factor multiplied by the change

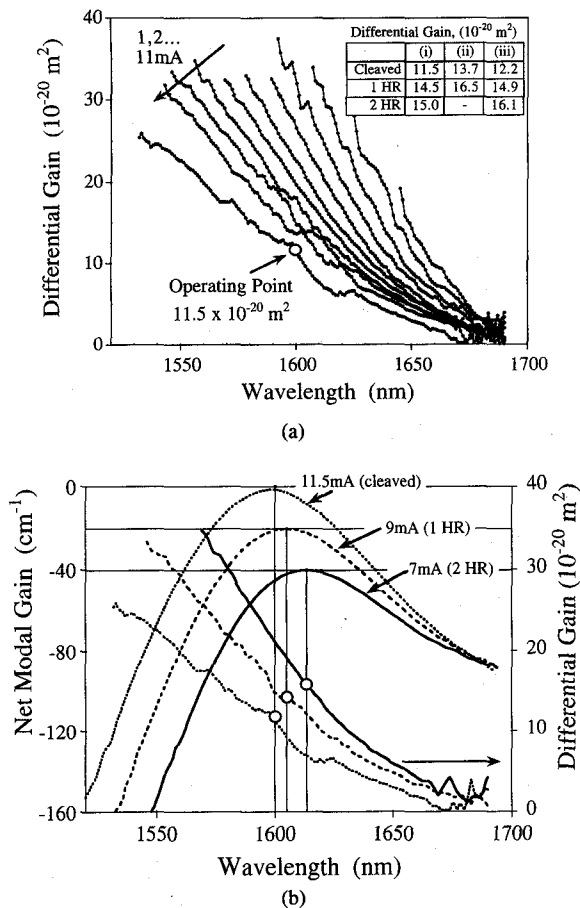


Fig. 3. (a) Differential gain versus wavelength at various bias currents and (b) gain and differential gain curves for the device as cleaved and after one and two HR coatings. The inset shows values of differential gain from i) dc measurements, ii) resonance frequency versus $(\text{output power})^{0.5}$, and iii) resonance frequency versus $(I - I_{th})^{0.5}$.

in index in the active region, and so “ α ” can be calculated. The error due to the assumption $\delta n_{\text{eff}} = \Gamma \delta n$ is of the order 10–20%, and in this case actually overestimates the value for “ α .” The results of “ α ” versus wavelength at various bias levels are shown in Fig. 4. This plot shows the typical high values of “ α ” seen at long wavelengths and low values at short wavelengths. This is expected from the change in differential gain versus wavelength, due to the movement of the gain peak toward short wavelengths caused by band filling as the bias is increased. The device in these experiments has an “ α ” value of 2 above threshold for the uncoated case, reducing to around 1.5 with two HR coatings. The most important consequence of this and the previous curves is for single-mode DFB lasers. These devices can be designed with their lasing mode detuned to the short wavelength side of the gain peak, where it is seen that “ α ” values down to 1 and below can be obtained using this active region structure and achievable device parameters.

In conclusion, we have described extensive dc measurements of the material parameters of p-doped, compressively

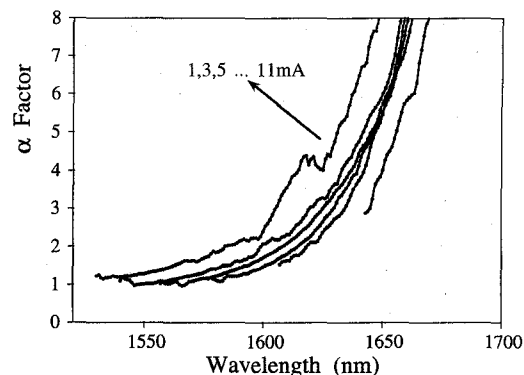


Fig. 4. Linewidth enhancement factor “ α ” versus wavelength at various bias currents.

strained MQW lasers. Extremely high differential gain and low threshold carrier density are found. These results are verified by high-speed resonance measurements, and the predictive power of the measured curves is shown through comparison of results before and after HR coatings. A simple measurement for the linewidth enhancement factor “ α ” is described, with results showing that using this MQW structure and correct device design, DFB lasers with “ α ” below 1 are possible.

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