Gain and Linewidth Enhancement Factor in InAs Quantum-Dot Laser Diodes

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***Abstract*—Amplified spontaneous emission measurements are investigated below threshold in InAs quantum-dot lasers emitting at 1.22 μm. The dot layer of the laser was grown in a strained quantum well (QW) on a GaAs substrate. Ground state gain is determined from cavity mode Fabry–Perot modulation. As the injection current increases, the gain rises super-linearly while changes in the index of refraction decrease. Below the onset of gain saturation, the linewidth enhancement factor is as small as 0.1, which is significantly lower than that reported for QW lasers.**

***Index Terms*—Linewidth enhancement factor, quantum dots, semiconductor laser.**

AN IMPORTANT, but often undesirable, property of semiconductor lasers is the degree to which variations in the carrier density N alter the index of refraction n of the active layer. This phenomena is often characterized by the linewidth enhancement parameter, $\alpha = -4\pi/\lambda(dn/dN)(dg/dN)^{-1}$ where g is the optical gain. Large values of α can result in antiguiding in narrow stripe lasers, self-focusing and filamentation in broad-area emitters, and chirp under modulation. For strained InGaAs single-quantum-well (QW) lasers operating near 980 nm, the value of α is typically 2 or higher at carrier densities corresponding to threshold [1], although 0.5, a record low, has been measured [2]. At the communications wavelengths of 1.3 and 1.55 μm, α is usually much higher unless modulation doping [3] or a large number of QW's are employed [4]. From the Kramers–Kronig relation, a symmetric gain spectrum will yield an α of zero at the peak gain because here the index of refraction will not change with carrier density. Since the density of states of a quantum dot (QD) is theoretically a series of delta-function spikes at the quantized energy levels, its gain spectrum ideally satisfies this criteria. Thus a substantial reduction in α should be realized by using QD lasers [5], [6].

In this letter, spectral and gain measurements are investigated using QD lasers that emit at 1.22 μm. Amplified spontaneous emission (ASE) profiles portray the physics of a structure with characteristics distinct from those of QW lasers. As a function of wavelength, the gain is relatively flat over a 3-nm range centered on the lasing line. The differential gain with respect to current, $\Delta g/\Delta I$, is initially small, but increases with current. Near threshold, however, the gain saturates and correspondingly, $\Delta g/\Delta I$ decreases. We find that before gain saturation begins to occur, α is 0.1. To our knowledge, this is the lowest α value experimentally measured to date.

The QD lasers feature a single layer of InAs QD's centered in a 100-Å $In_{0.2}Ga_{0.8}As$ QW structure and have been described elsewhere [7], [8]. The "dots-in-well" (DWELL) design is analogous to the common separate confinement heterostructure of typical QW lasers but on a smaller scale. Material was processed into 30-μm ridge waveguide lasers, which is in an intermediate width between narrow stripe devices and broad area lasers. These devices are predominantly single lateral mode while simultaneously being wide enough for a large signal and reasonably uniform current injection, which improves the accuracy in determining α [1].

1.5-mm cavity length lasers are biased in pulsed mode (0.3-μs pulse and 1.5% duty cycle) with a Hewlett-Packard 8114A pulse generator. The lasers did not show any detectable evidence of wavelength shifts due to heating under these conditions. The collimated light is modulated with a Stanford Research Systems SR540 optical chopper, then focussed onto the entrance slit of a 1.3-m Acton Research Corp. monochromator. The entrance and exit slits are set at 40 μm and a 1200 lines/mm grating is used. The effective resolution is approximately 0.1 Å. Exiting light is collected with a cooled InGaAs photodetector, and a Stanford Research Systems SRS830 lock-in amplifier measures the generated photocurrent.

Gain and refractive index were determined from below-threshold ASE spectra [9], [10]. The net modal gain, g, is extracted from the peak to valley ratio of subthreshold Fabry-Perot oscillations using $g = (1/L)\ \ln[r^{-1}(\sqrt{x}-1)(\sqrt{x}+1)^{-1}]$ where L is the cavity length, x is the ratio of peak to valley heights, and r is the facet reflectivity. Using $\Delta g/\Delta I$ for the differential gain and $\Delta n/\Delta I = -(n/\lambda)\Delta\lambda/\Delta I$ for differential index, where ΔI is the current increment, the experimental value for α is $-(4\pi n/\lambda^2)\Delta\lambda/\Delta g$.

In order to reduce the error in measuring wavelength shifts, the current was stepped incrementally at each wavelength before scanning the monochromator to its subsequent position. By proceeding in this manner, as opposed to sweeping the monochromator for each current bias, no drift can be attributed to the monochromator, and the observed wavelength shifts with respect to current $\Delta\lambda/\Delta I$, are revealed more accurately.

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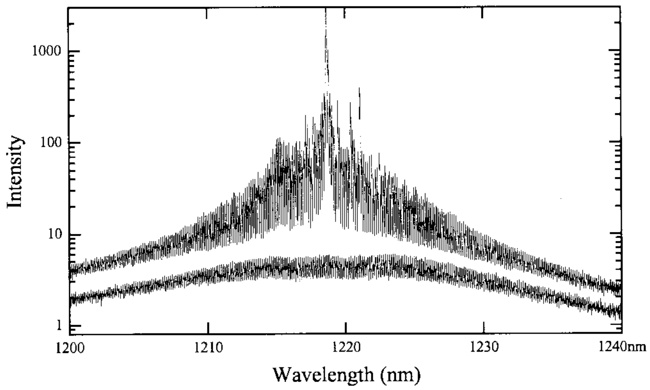

Fig. 1. QD amplified spontaneous emission spectra at 45 and 50 mA (just below threshold) of a 1.5-mm cavity length laser show a nearly symmetric shape in the depth of the Fabry–Perot fringes. The average intensity at shorter wavelengths increases more than longer ones due to the influence of excited states.

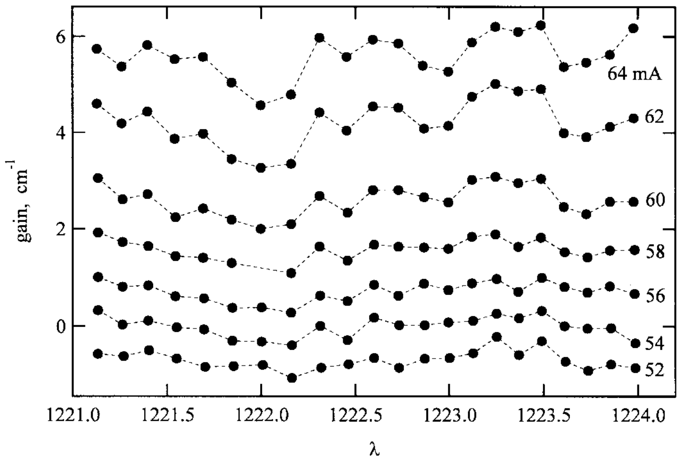

Fig. 2. Gain versus λ derived from the ratio of peak to valley heights for 52 to 64 mA currents This particular 1.5 mm laser has $I_{\rm th} = 73$ mA. The graph markers denote the position of the fringe peaks. In contrast to QW lasers, the gain across this 3-nm sweep is nearly constant.

Due to the relatively long length of the QD lasers, accuracy in determining wavelength shifts and peaks/valleys in the ASE spectrum was limited largely by the resolving power of the monochromator.

Fig. 1 shows a typical spontaneous emission (SE) profile from 1.2 to 1.24 μm for currents below and near lasing threshold. The spectrum is centered on ground state transitions. Excited state energy levels correspond to 1.05-μm transitions, as observed from short cavity $(L < 1$ mm) lasers. 1.4-Å Fabry–Perot fringes are clearly revealed in the figure. Overall the profiles possess a strikingly symmetric aspect with respect to the 1218.6-nm central line (The same symmetry exists when plotted as a function of energy.). A determination of the net modal gain from this data, not shown, also shows a high degree of near-Gaussian symmetry. The profile is a legacy of the random size distribution of the QD's. On closer observation, with respect to the central peak, the average intensity is greater at shorter wavelengths than at longer ones. Initially, carriers are more likely to fill the ground state energy levels of all dots and in particular that of the larger dots (corresponding to the lowest energy states available). Subsequent carrier distribution results in population of the smaller dots and excited energy states. In addition, we have observed evidence of homogenous broadening in efficiency measurements of QD lasers subjected to external feedback from a grating. These results will be presented elsewhere. The combination results in a blue shifting of the spectral center and the greater intensity levels at shorter wavelengths. This also breaks the symmetry of the overall gain profile and prevents the α-parameter from being identically zero.

A plot of the measured gain versus wavelength is shown in Fig. 2 for currents of 52 to 64 mA with 2-mA steps between data sets $(I_{\rm th} = 73$ mA). This laser is different from the one used to produce the spectrum in Fig. 1, and the sweep is centered on this particular laser's center line. The dot markers in Fig. 2 are placed to indicate the location of the Fabry–Perot peaks. From 1221.0 to 1224.2 nm, the gain is relatively flat for each current set. This result is again due to the size distribution of the QD's. This is quite different from QW lasers, which would show a definite gain rolloff across this range. The peak gain at 88% threshold is 6 cm^{-1}. A net gain of 7 cm^{-1} was

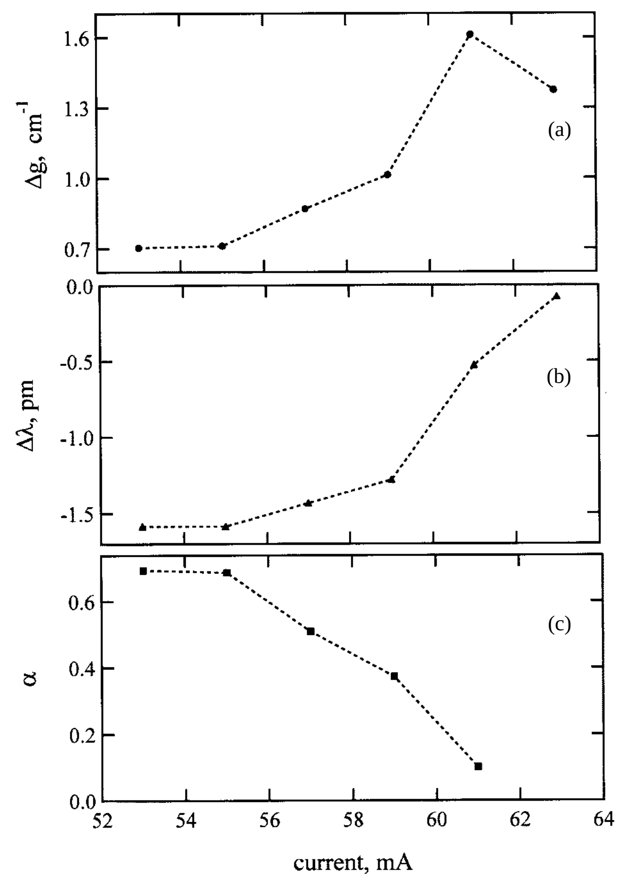

Fig. 3. (a) Average Δg as a function of current. The differential gain begins to rise rapidly at $\sim$79% $I_{\rm th}$ and gain saturation begins to occur above 64 mA. (b) $\Delta\lambda$ is relatively large for low bias, but approaches zero at larger currents. (c) α, as a result, becomes 0.1 at 61 mA.

measured at the lasing threshold. Considering the experimental error noted above, this value is consistent with our maximum modal gain estimate of 7.5–8.5 cm^{-1} (taking into account the internal loss) determined in [7].

Fig. 3(a) shows the evolution of the differential gain, $\Delta g/\Delta I$, Fig. 3(b) shows the wavelength shift, $\Delta\lambda/\Delta I$, and

Fig. 3(c) the resulting α parameter for the same laser as in Fig. 2. $\Delta g/\Delta I$ is obtained by averaging the gain over the 3-nm wavelength range shown in Fig. 2. A curve fit to the correlation function determined $\Delta\lambda/\Delta I$ between successive data sets. In these plots, the abscissa of the graph markers are placed at the average of the two current levels used. Due to the low threshold current density of the QD laser, useful data can only be taken over a relatively small range of current levels. Antireflection coatings could be applied to increase the threshold current density, although in the QD laser this would be of limited benefit since excited state levels become populated at higher current densities, altering the entire spectrum.

At the lowest current densities measured not only is the gain low, but the differential gain is low as well. At a current of roughly $0.79 I_{\rm th}$, however, the differential gain increases dramatically as seen in Fig. 3(a). This is followed by gain saturation and the corresponding decrease in differential gain as the current nears threshold as seen by the last point in Fig. 3(a). Thus, with respect to current density, the gain shows an inflexion point. These QD trends are in contrast to that of QW structures. In the latter case, the differential gain is highest at low current density, gradually decreasing with increasing density as states associated with the $n = 1$ transition fill.

A qualitative model can be used to explain the trends in the gain and differential gain and underscore the difference between QD and QW active regions [11], [12]. Assuming that electrons and holes populate only the ground state of the dots, that the filling is random, and that charge neutrality in the dot is not required, the probability of dot occupation by either an electron or hole is n_c/n_t, where n_c is the 2-D density of electrons or holes, and n_t is the dot density. Since dot filling is biased toward the larger dots, the assumptions are not strictly accurate. However, this will not affect the general result. Here the gain is a function of the ground state occupation probability. Since electrons and holes do not necessarily fill the dots in pairs, the gain is small until a significant number of dots are filled, at which point it increases super-linearly as shown in Figs. 2 and 3(a). In this scenario, our results are consistent with electroluminescence efficiency measurements described by Huffaker in [13]. In contrast, QW laser theory, using quasi-Fermi levels and a staircase-like density of states function, yields a sublinear increase in gain with current.

In Fig. 3(b), $\Delta\lambda$ slowly decreases in magnitude up to the point where a large increase in the gain occurs. It then rapidly approaches zero as the current is incremented. We have also observed that for wavelengths both longer and shorter than the central region, $\Delta\lambda$ was always negative for currents below threshold. Wavelength shifts in QW structures are generally much larger in magnitude and reduce with increasing current in a much more gradual fashion.

The linewidth enhancement factor decreases to 0.1 at a current near 61 mA, as seen in Fig. 3(c). This value is obtained at a point sufficiently below threshold so that the gain is not saturating and, correspondingly, $\Delta\lambda$ is not negligible. To our knowledge, this is the lowest measured α value experimentally measured to date. Other QD lasers from the same wafer exhibit similar characteristics as the one shown in Figs. 2 and 3 and yield similar though slightly larger values for α across this current range.

In conclusion, edge-emitted amplified spontaneous emission from QD lasers whose dot layer is grown in a strained QW has been studied spectrally. Gain, differential gain, and wavelength shifts were measured for subthreshold current levels. In contrast to QW lasers whose differential gain decreases on increase of carrier density, QD devices show an increase in differential gain up to the point of gain saturation. This unique characteristic can be explained by considering that the dots are filled randomly. As a result, a linewidth enhancement factor of 0.1 has been observed in a 1.5-mm laser with a 30-μm stripe width. This feature is a benefit of the nearly symmetric gain spectrum created by the combination of the delta function density of states and the random size distribution of the dots. Theoretical investigations of filamentation in broad area semiconductor lasers predict that the α values measured in this study will not provoke filamentation regardless of the pumping level [14]. Thus QD lasers are promising devices for high power semiconductor lasers and amplifiers.

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