Spectral and dynamic characteristics of buried-heterostructure single quantum well (Al,Ga)As lasers

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(Received 21 March 1988; accepted for publication 17 May 1988)

We demonstrate that, as predicted, (Al,Ga)As single quantum well (SQW) lasers have substantially narrower spectral linewidths than bulk double-heterostructure lasers. We have observed a further major reduction ($>3\times$) in the linewidth of these SQW lasers when the facet reflectivities are enhanced. This observation is explained theoretically on the basis of the very low losses in coated SQW lasers and the value of the spontaneous emission factor at low threshold currents. We also report on the modulation frequency response parameter of these SQW lasers.

Buried-heterostructure graded-index separate-confinement heterostructure (BH GRIN SCH) single quantum well (SQW) (Al,Ga)As lasers with high-reflectivity end facet coatings have recently been shown to possess extremely low threshold currents.[1-3] High-reflectivity coatings produce a proportionately larger reduction in the threshold current of quantum well (QW) lasers compared to conventional ones caused by much lower transparency current.[1] SQW stripe lasers with high-reflectivity coatings could play a significant role in the development of optical supercomputers, which will rely on semiconductor lasers for their internal communication. The number of lasers that may be involved is so large that ultralow threshold currents are needed. The dynamic characteristics of such lasers are clearly of interest, since this application requires high-frequency modulation. In addition, the spectral linewidth, which is expected to be much narrower than that of conventional double-heterostructure lasers,[4] is important for other applications requiring highly coherent laser sources. In this letter we report on the spectral linewidth and direction modulation bandwidth of BH GRIN SCH SQW (Al,Ga)As lasers with and without high-reflectivity coatings.

The buried-heterostructure GRIN SCH SQW lasers were fabricated in a two-step growth process as described in Ref. 1. The basic structure employed was a 70 Å QW with a graded-index structure approximately 0.4 μm thick placed symmetrically around the SQW. Broad-area devices 500 μm long and 100 μm wide fabricated from this material had threshold current densities of ~ 300 A/cm^2 and external differential quantum efficiencies of $\sim 82\%$. The buried structure was formed with a liquid phase epitaxy (Al,Ga)As regrowth for optical and electrical confinement around an active layer stripe of ~ 4 μm width. These devices were found to have average internal losses (including waveguiding losses) of ~ 7 cm^{-1}. Typically 250-μm-long stripe lasers with uncoated (90% reflective) end facets had cw threshold currents of ~ 7 mA (about 3 mA) and external differential quantum efficiencies of $\sim 70\%$ (about 37%).

The spectral linewidth of these lasers is of interest since it is a measure of the phase noise in the laser output. The spectral linewidth of a semiconductor laser is[5,6]

$$2\Gamma = v_g^2 E_L [\alpha_i - (1/2L)\ln R_1R_2] \times \frac{(-1/2L)\ln(R_1R_2)n_{sp}(1+\alpha^2)}{4\pi P_1[1+(\sqrt{R_1}/\sqrt{R_2})(1-R_2)/(1-R_1)]}, \quad (1)$$

where 2Γ is the full width at half-maximum of the lasing mode at photon energy E_L, v_g is the group velocity, α_i is the internal loss, L is the laser cavity length, R_1 and R_2 are the end facet reflectivities, P_1 is the output power at the facet with reflectivity R_1, and n_{sp} is the spontaneous emission factor. $n_{sp} = \{1-\exp[(E_L+F_v-F_c)/kT]\}^{-1}$, where F_c and F_v are the quasi-Fermi levels of the conduction and valence bands, k is the Boltzmann constant, and T is the temperature. Approximating the energy levels of the SQW with those of an infinitely deep well was found to cause significant error[7] in n_{sp}; consequently, the actual energy levels, which were computed by numerically solving the Schrödinger equation, were used in calculating n_{sp}. At very low carrier densities (near transparency), n_{sp} is large, but it approaches 1 as the carrier density increases. In SQW lasers n_{sp} is calculated to approach 1 more quickly than in bulk double-heterostructure lasers.[4] α is the linewidth enhancement factor[5,6]:

$$\alpha = \frac{d\chi_R(n,E_L)/dn}{d\chi_I(n,E_L)/dn}, \quad (2)$$

where n is the carrier density, and χ_R and χ_I are the real and imaginary parts of the electron susceptibility.

SQW lasers are expected to have narrower linewidths than conventional double-heterostructure lasers since α is calculated to be significantly smaller[4] for SQW lasers. The much smaller internal loss[7] (<2 cm^{-1} in the best SQW's) and the smaller values of n_{sp} should also contribute. The linewidth of a multiquantum well laser, which has been measured in the distributed feedback structure,[8] is narrow for the same reasons as that in a SQW. Calculations of α based on rigorous k selection and accounting for intraband relaxations by including a Lorentzian line shape function[9] with an intraband relaxation time of 0.2 ps predict $|\alpha| \sim 2.3$ for the present stripe lasers.

To understand the dramatic effect of facet reflectivity on the linewidth in a QW laser consider (1) when

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$R_1 = R_2 = R$:

$$2\Gamma = v_g^2 E_L [\alpha_i - (1/L)\ln R] \times (-1/L)(\ln R) n_{sp}(1+\alpha^2)/8\pi P_1. \quad (3)$$

Examining (3), it is clear that as $R \to 1$, 2Γ is reduced; this effect has already been appreciated for conventional double-heterostructure lasers.[10] The reduction is significantly greater in QW lasers because of their much smaller internal losses; however, n_{sp} limits the reduction since it increases exponentially as the threshold current density decreases. Therefore, in a SQW with enhanced facet reflectivities and low loss, the linewidth will be dramatically reduced, but for very high facet reflectivities the increase in n_{sp} will become a significant limiting factor in the reduction. While $|\alpha|$ is expected to decrease slightly at lower threshold current densities,[11] our calculations indicate that this will not be a significant factor compared to the end loss and n_{sp}.

The spectral linewidths of uncoated and coated buried heterostructure GRIN SCH SQW lasers at room temperature were measured with a scanning Fabry–Perot interferometer. Great care was taken to prevent optical feedback into the lasers by isolating them from the Fabry–Perot interferometer with an optical isolator and neutral density filters with at least 10^4 attenuation for all measurements. A spectrometer was used to verify single-mode laser operation for the power ranges at which linewidths were measured.

Figure 1 shows the linewidth of a typical GRIN SCH SQW with and without coatings as a function of $1/P_1$. Results for this device and others are tabulated in Table I. The measured slope, 28.3 MHz mW, as a function of $1/P_1$ for uncoated lasers, is significantly smaller than that of bulk double-heterostructure stripe lasers. For instance, Welford and Mooradian[12] measured 74.7 MHz mW at 273 K for Mitsubishi transverse junction stripe lasers.

Figure 1 shows that when the end facet reflectivities were increased 85% and 93%, the slope was reduced from 28.3 to 5.9 MHz mW, but the intercept increased to 2.2 MHz. The narrowest linewidth measured for this device was ~6 MHz at 1.3 mW. All the coated SQW lasers (Table I) examined had significant nonzero intercepts. A nonzero intercept is not predicted by (1), but has been observed experimentally for other semiconductor lasers[9,13] and has been attributed to several possible mechanisms.[14,15] Although very narrow linewidths have been measured for lasers with coupled cavities,[16] the present linewidth slopes $2\Gamma P_1$ are, to the best of our knowledge, the smallest measured for a solitary semiconductor laser at room temperature. Examination of Table I reveals that for the most highly coated devices the increase in n_{sp} becomes a significant factor as predicted theoretically.

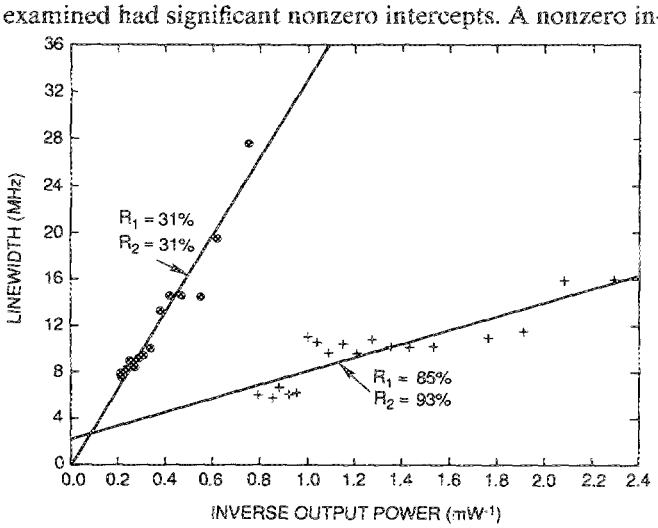

FIG. 1. Spectral linewidth as a function of the reciprocal of the output power at facet with reflectivity R_1 for an uncoated buried heterostructure GRIN SCH SQW laser and for the *same* laser with coated facet reflectivities $R_1 = 85\%$ and $R_2 = 93\%$.

TABLE I. Summary of measured data and theoretical estimates for the spectral linewidth of 250-μm-long buried-heterostructure GRIN SCH SQW lasers with and without high-reflectivity facet coatings. The theoretical estimate of $|\alpha|$ used is 2.3.

Reflectivity R_1 / R_2	31% / 31%	31% / 92%	57% / 89%	85% / 93%	92% / 92%
$(-1/2L)\ln R_1R_2$ (cm^{-1})	46.8	25.1	13.6	4.7	3.3
n_{sp} Theory	1.0	1.4	1.9	7.3	8.2
$n_{sp}(1+\alpha^2)$ Theory	6.3	8.8	12.0	45.9	51.6
$2\Gamma P_1$ (MHz mW) Theory	10.7	8.1	2.9	0.79	0.34
$2\Gamma P_1$ (MHz mW) Experiment	28.3	17.5	5.3	5.9	2.1
Intercept (MHz) Experiment	0.9	5.9	2.7	2.2	6.8
$n_{sp}(1+\alpha^2)$ Experiment	17.1	17.9	17.9	120.7	95.4
$\|\alpha\|$ Experiment	3.9	3.4	2.9	3.9	3.3

While SQW's have significantly narrower linewidths than bulk double heterostructures, the linewidths are not as narrow as predicted theoretically. If the calculated value for n_{sp} is accurate, $|\alpha|$ for uncoated devices is 3.9. It is reasonable that $|\alpha|$ is somewhat larger than predicted since the calculations neglect the free-carrier absorption contribution to $\chi_R(n,E_L)$. The interband component is normally dominant[17]; however, the free-carrier contribution is expected to be dependent on the device structure.[18] In bulk BH (Al,Ga)As lasers, $|\alpha|$ has been measured to be 6.2,[17] which is significantly larger than what is measured for other stripe bulk (Al,Ga)As heterostructure lasers. Therefore, this discrepancy may be due to the relatively large free-carrier contribution in a buried stripe. The present results for uncoated devices confirm that $|\alpha|$ is reduced in SQW lasers. It is likely that other SQW stripe laser structures might have even narrower linewidths because of smaller free-carrier contributions to $|\alpha|$. In the most highly coated devices, the value of $|\alpha|$ depends strongly on how much n_{sp} is increased; however, the results suggest that, as expected, $|\alpha|$ is decreased slightly from its value in uncoated lasers.

The high-frequency modulation characteristics of buried-heterostructure GRIN SCH SQW's are encouraging.[2,19] The relaxation oscillation frequency f_r, which limits the useful modulation bandwidth of a semiconductor laser,[20] has not been measured previously for these devices:

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$$f_r = (1/2\pi)\sqrt{A(P_0/\tau_p)}, \quad (4)$$

where A is the optical gain parameter, which is proportional to the differential gain, P_0 is the stationary photon density inside the lasing cavity, and τ_p is the photon lifetime. $\tau_p = n_r/c[\alpha_i - (1/2L)\ln R_1R_2]$, where n_r is the refractive index and c is the speed of light.

For frequency response measurements, the lasers were mounted in a microwave package, and dc bias current I and microwave signal were applied through a bias T. The frequency response was measured with a high-speed *p-i-n* photodiode. In Fig. 2 the measured f_r is shown as a function of $\sqrt{I/I_{th} - 1}$ (where I_{th} is the threshold current) for an uncoated SQW laser and one with $R_1 = 57\%$ and $R_2 = 89\%$. The measured values of f_r reached 5 GHz for both devices.

f_r for the coated laser is very similar to that of the uncoated laser. One might have expected a dramatic change, since the differential gain and photon density in the uncoated device are lower. (The differential gain is reduced because of gain saturation.[4]) However, τ_p, which is inversely proportional to the mirror loss, is also reduced and tends to counteract the effects of differential gain and photon density.

On the basis of the measured values of f_r, A in the uncoated laser is 3.3×10^{-6} cm^3 s^{-1}, which is very similar to $A(2.8\times10^{-6}$ cm^3 s$^{-1})$ in conventional semiconductor lasers.[21] In the device with $R_1 = 57\%$ and $R_2 = 89\%$, A increases to 6.2×10^{-6} cm^3 s^{-1}. While the experimental values of A fit the theoretical prediction of higher differential gain in a QW when the threshold gain is decreased, the actual numbers are higher than what is prediced theoretically by calculations in which intraband relaxations were accounted for with Lorentzian line shape function.[4] It is possible that this discrepancy is due to underestimation of the gain caused by the Lorentzian line shape function.[22]

In conclusion, as predicted,[4] SQW lasers have much narrower spectral linewidths than bulk double-heterostructure lasers. SQW lasers with high-reflectivity coatings have dramatically narrower linewidths as a result of their low losses. Linewidths as narrow as 6 MHz at 1.3 mW output power were measured. If allowance is made for the free-carrier contribution to the linewidth enhancement factor, the experimental results fit theoretical predictions well. The calculations must be considered to be only estimates, however, since they depend on gain calculations which tend to underestimate the value of the differential gain inferred from measurements of relaxation oscillation frequencies. Values reaching 5 GHz were measured for the relaxation oscillation frequency of these lasers. As expected, the coated devices with lower losses and lower threshold currents show a higher differential gain than the uncoated devices because of gain saturation at the higher threshold currents.

This work was supported by the National Science Foundation, the Office of Naval Research, and the Air Force Office of Scientific Research. The authors would like to acknowledge discussions with N. Bar-Chaim of Ortel Corporation. One author (M.M.) gratefully acknowledges support from a Newport Research Award.

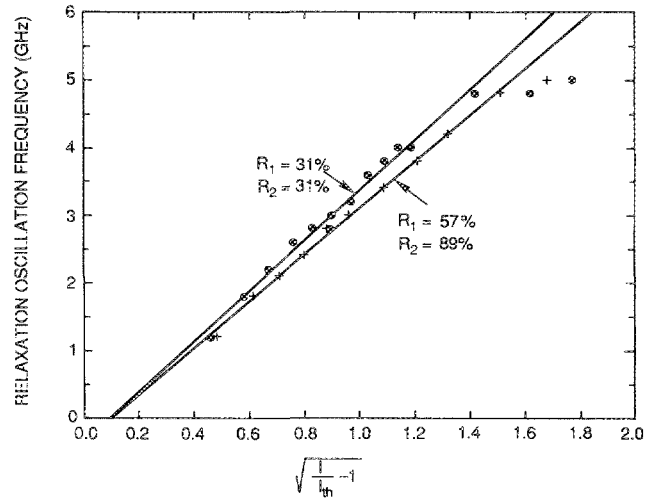

FIG. 2. Relaxation oscillation frequency as a function of $\sqrt{I/I_{th} - 1}$ for an uncoated buried heterostructure GRIN SCH SQW laser and one with $R_1 = 57\%$ and $R_2 = 89\%$.

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