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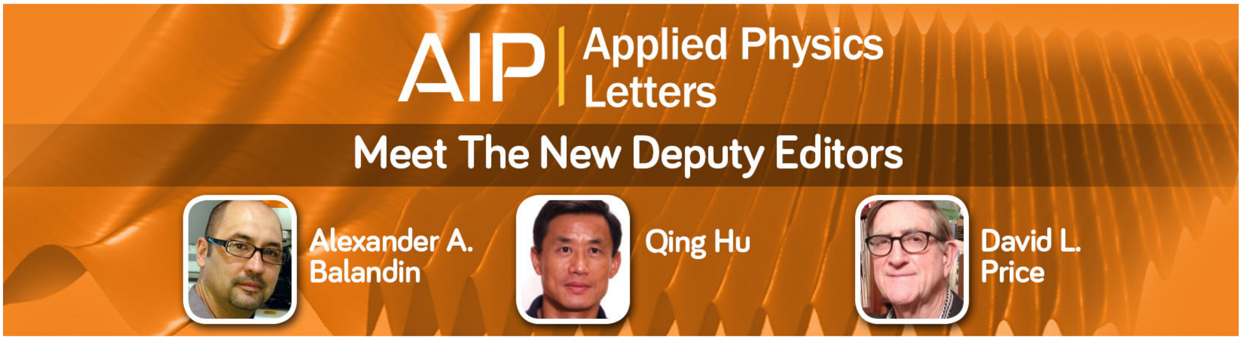

Nonequilibrium effects in quantum well lasers

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We present a simple technique of measuring the effect of the finite capture time of carriers in quantum well lasers on the homogeneity of the gain. The effect is measured using an extended cavity laser configuration in which we control the feedback level and compare the two extreme cases of a laser and a nonlasing amplifying gain medium. Broadband measurements of the spontaneous emission at energies near the top of the well and above the barriers show an inhomogeneous gain saturation which depends on the photon density inside the cavity. The results agree with a simple model for carrier injection in quantum well lasers.

The scope of research on optical and electronic properties of quantum well (QW) structures spans from research on basic physical processes[1-3] to device-oriented phenomena.[4-10] In many cases, fundamental processes are paramount to proper device operation. A key issue to be addressed, therefore, is how do basic QW properties manifest themselves in the context of practical device structures. The issue is particularly critical for QW diode lasers and amplifiers operating at room temperature and under electrical excitation. For large drive currents, the high carrier densities together with stimulated emission (which is key to the operation of these devices) influence all basic physical mechanisms. Among the fundamental QW properties of interest, the process of carrier transfer from bulk states (in the barrier and confinement regions) into the quantized states in the well (i.e., capture into the well)[2,8,11] plays a major role in determining QW laser characteristics.[5-10,12] This capture process has a picosecond scale time constant associated with it.[11] It has already been pointed out that this short, but finite, capture time has a profound effect on QW laser modulation properties[5,12] and on their dc characteristics.[9,10]

Dynamic processes with relaxation times on the picosecond time scale (similar to QW capture) may affect static device characteristics. At the same time, static measurements are sometimes capable of indicating fast processes. For example, Ogasawara *et al.*[2] used luminescence spectra of GaAs/AlGaAs quantum wells to demonstrate oscillations of the capture time with well thickness using low-temperature photoluminescence from energies higher than the well under cw optical excitation. Also, Yamanishi *et al.*[13] demonstrated spectral hole burning at the high-energy tails of InGaAsP lasers by comparing spontaneous emission spectra at those high energies under lasing and nonlasing conditions. Here, we demonstrate inhomogeneous gain saturation between the well and bulk states in QW lasers. Although this inhomogeneity is related to the fast (several picosecond) total capture time (consisting of the transport and local capture times[4]), the effect is determined using static measurements of spontaneous emission spectra. The inhomogeneous gain saturation results from an accumulation of carriers outside the well.[5,14] The carrier accumulation is due to the inability of carriers in the bulk states to relax into the quantized states at the rate they are removed from the well. It is clear that the carrier accumulation (amount of inhomogeneity) depends on the ratio between the capture time and the carrier lifetime in the well. This accumulation is often referred to as an "injection bottleneck."[14]

A model for carrier injection in QW lasers is presented in Ref. 12. The model[12] is a simple version of the model described in Ref. 8. It is used here to give a qualitative physical picture of the gain inhomogeneity in QW lasers. Briefly, the carrier injection process is described using three levels (Fig. 1): (1) the diffusion level (with N_d number of carriers) into which the carriers are injected through the contacts; these carriers which are at energies higher than the QW diffuse towards the wells. (2) The capture level (with carrier number N_c) represents the area above the wells. Carriers diffuse into this level and are removed from it when they are captured into the well. (3) The gain level (where the number of carriers is N_g) that represents the carriers in the QW which interact with the photons. The levels N_d and N_c reach steady state through transport mechanisms, while the levels N_c and N_g reach steady state through capture and emission into and from the well. The rate equation describing the carriers in the QW (N_g) is

$$\frac{dN_g}{dt}=\frac{N_C\eta_F-N_g}{\tau_C}-G(N_g,S)-\frac{N_g}{\tau_n}=\frac{N_C\eta_F-N_g}{\tau_C}-\frac{N_g}{\tau_{\mathrm{neff}}}. \tag{1}$$

Here, $N_C\eta_F-N_g/\tau_C$ is the net capture rate, τ_c/η_F is the capture time, η_F is the equilibrium ratio (for $\tau_c=0$) between N_c and N_g, determined by Fermi statistics, τ_n is the spontaneous carrier lifetime in the well, G is the nonlinear gain, S is the photon density in the cavity, and τ_{neff} is an effective carrier lifetime in the well. At steady state, $d/dt=0$ so that

$$N_c=\frac{N_g}{\eta_F}\left(1+\frac{\tau_c}{\tau_{\mathrm{neff}}}\right). \tag{2}$$

We note that since $\tau_c/\tau_{\mathrm{neff}}>0$, the number of carriers at energies higher than the well differs from the equilibrium

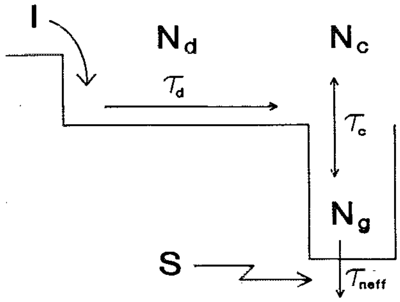

FIG. 1. Schematic description of the capture process.

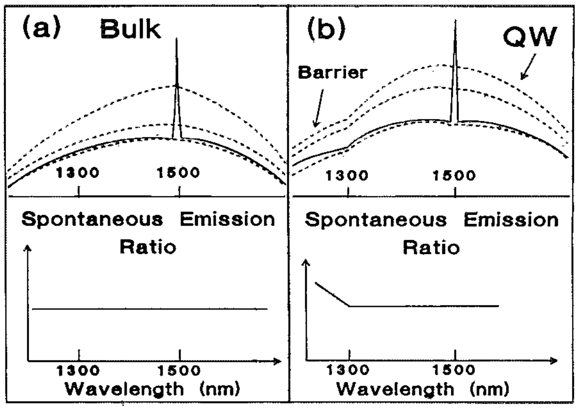

FIG. 3. Conceptual description of the process to determine the ASE RATIO. (a) Bulk lasers, (b) QW lasers.

number (which is $N_C = N_g/\eta_F$). Moreover, this deviation increases when the carrier lifetime in the well shortens. Obviously, when N_C increases, N_d increases as well.

The effect of the capture time on the spontaneous emission spectrum at high energies is studied in a MQW extended cavity laser using a simple experimental setup, as shown in Fig. 2. As will be shown, the spontaneous emission spectrum is a good indicator for the carrier accumulation effect. In the experiments presented here, we control carrier accumulation at energies above the well (N_C and N_d) by changing the carrier lifetime in the well while the total capture time remains essentially constant. This is achieved by controlling the operating conditions (drive current and feedback level) of the extended cavity laser.

In order to examine the homogeneity of the gain, we measure the spontaneous emission spectra at the energy range from the top of the well up to the bulk states according to the following procedure: (1) The spontaneous emission spectrum ASE_l is measured under lasing conditions. (2) The laser feedback is blocked and spontaneous emission spectra ASE_i are remeasured at several drive currents, all smaller than the lasing current. (3) At each drive current, we calculate the ratio $\text{ASE}_l/\text{ASE}_i$. The current for which this ratio equals one is identified and the term ASE RATIO is then defined as the ratio $\text{ASE}_l/\text{ASE}_i$ **for that particular current**. The physical concept behind the above procedure is as follows. Spontaneous emission is proportional to the number of carriers, so that for two equal spontaneous emission spectra, the number of carriers is the same. In step (3) above, we look for a drive current for which the number of carriers in the nonlasing case (long carrier lifetime) equals the number of carriers in the lasing case (short carrier lifetime). This technique is similar to the one described in Ref. 15. Here, we use the laser line as the saturating pump signal and the spontaneous emission as a broad band probe. Moreover, unlike Ref. 15 which plots the relevant gain spectra, we present the ASE RATIO, which is the ratio of the corresponding spontaneous emission spectra. For a bulk semiconductor gain medium, the gain saturation is homogeneous[15] and the ASE RATIO equals one for all wavelengths which are not too close to the lasing wavelength. This is shown conceptually in Fig. 3(a). On the other hand, for a QW laser (where an injection bottleneck exists) the ASE RATIO equals one for wavelengths corresponding to energies inside the wells but is larger for wavelengths shorter than the wavelength corresponding to the barrier band gap (where carriers accumulate). This increase of slope is due to the fact that the carrier lifetime in the well is reduced under lasing conditions (ASE_l) and the accumulation of carriers due to finite capture time is more pronounced compared with the nonlasing case (ASE_i). The change of slope in the curve at the barrier wavelength is shown conceptually in Fig. 3(b).

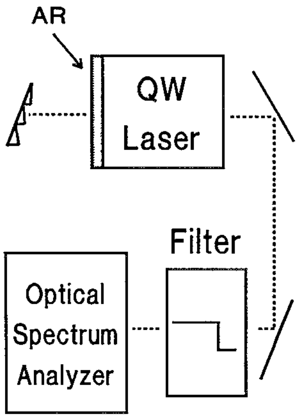

FIG. 2. Schematic of the experimental setup.

The experimental setup (Fig. 2) is very simple. It consists of an extended cavity laser whose output is filtered by a short pass filter and then measured using an optical spectrum analyzer. The short pass filter is essential in order to achieve high rejection of the lasing wavelength. The lasers used in this experiment were of three kinds. A bulk 1.5 μm laser and two types of 1.5 μm InGaAsP/InGaAs MQW lasers. The MQW lasers had different barrier band gap wavelengths, 1300 nm (laser Q1300) and 1360 nm (laser Q1360). All lasers were antireflection (AR) coated on one facet. Laser Q1300 was a MQW laser grown by a hybrid low-pressure (LP)/atmospheric-pressure (AP) metal organic vapor phase epitaxy (MOVPE) process. The waveguide portion consisting of the four wells and the separate confinement heterostructure quaternary layers were grown by LPMOVPE (100 Torr) at 625 °C, using 100% PH3 and

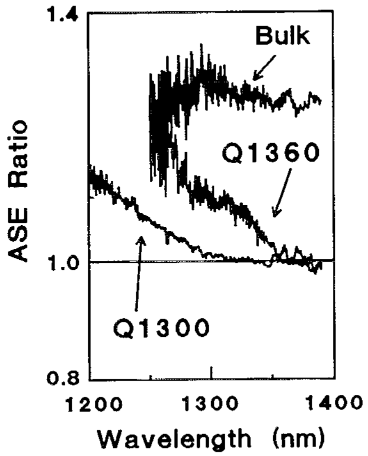

FIG. 4. Measured ASE RATIOS for a bulk and for two types of QW lasers.

AsH3, and trimethyl-gallium and ethyl-dimethyl indium. The thick ($\approx 1.5\ \mu$m) *p*-type InP top layer and the *p*-type InGaAsP contact layer was grown by APMOVPE at 650 °C. 2–3 μm-wide ridges were etched to define the index-guided laser stripes using standard photolithographic and wet chemical etching techniques. Thick ($\approx 2\ \mu$m) semi-insulating InP:Fe current blocking layers were finally grown around the etched ridges by APMOVPE. Laser Q1360 had a similar structure.

The experimental results are presented in Figs. 4 and 5. Figure 4 compares measured ASE RATIOS for a bulk laser and for the two QW lasers. The measured results are in excellent agreement with the predictions of Fig. 3, and in the case of a bulk semiconductor, also with Ref. 15. The data clearly show the change of slope in the ASE ratio curves of the two QW lasers at the proper wavelengths.

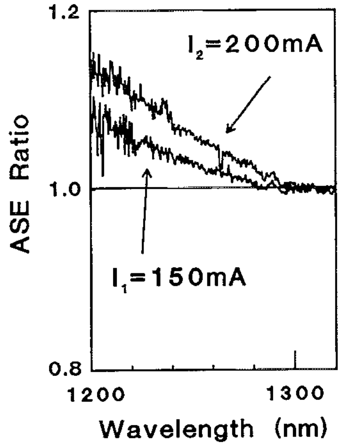

FIG. 5. Measurements of the ASE RATIO dependence of the lasing drive current.

In Fig. 5, we show the effect of changing the carrier lifetime in the well on the ASE RATIO. The experiment was performed using laser Q1300. We control the lifetime by changing the lasing drive current and we obtain the ASE RATIO curve separately for each lasing current. At the higher current, the lifetime is shorter, the carrier injection bottleneck increases, and the slope of the ASE RATIO curve is larger. Obviously, the two curves change slope at the same wavelength, 1300 nm. These experimental results are in a good agreement with the model presented in Ref. 12 [see Eq. (2) above].

In conclusion, we have presented a novel technique of measuring the effect of the finite capture time in QW lasers on the homogeneity of the gain saturation. We showed that the inhomogeneity results from an imbalance between the capture rate into the wells and the photon density dependent carrier lifetime in the well. This manifests itself in a carrier injection bottleneck, and hence, a structure and bias dependent gain nonlinearity.[12] We note that in the above experiment we compared two cases where only the QW lifetime was controlled. By comparing different structures with different capture times, one can study, using this technique, the variation of the capture time with the structural parameters.

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