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Femtosecond gain dynamics in InGaAs/AlGaAs strained-layer single-quantum-well diode lasers

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We report the first investigation of femtosecond gain dynamics in InGaAs/AlGaAs strained-layer single-quantum-well diode lasers using a multiple-wavelength pump probe technique. Studies demonstrate that carrier temperature changes from free-carrier absorption and stimulated transitions strongly govern transient gain dynamics. The energy of the pump wavelength relative to the transparency point determines which processes dominate the transient response. Stimulated carrier cooling is observed for the first time in these materials.

The study of femtosecond gain dynamics in laser diodes plays an important role in understanding laser linewidth, modulation bandwidth, amplification, and short-pulse generation.[1–6] Pump probe measurements of nonlinear gain dynamics have been performed in bulk GaAs,[7–9] bulk InGaAsP,[10] InGaAsP multiple-quantum-well (MQW),[11,12] and InGaAs/InGaAsP strained-layer MQW amplifiers.[13] Dynamic carrier temperature changes influence gain dynamics on the 1 ps time scale. These temperature changes can be produced by free-carrier absorption, stimulated transitions, and two-photon absorption. Previous studies have shown that free-carrier absorption plays a dominant role in carrier heating.

Recently, we have shown that both free-carrier absorption and stimulated transitions contribute to carrier heating in InGaAs/AlGaAs strained-layer single-quantum-well (SQW) diode lasers.[14] In this letter, we present the first investigation of gain dynamics in an InGaAs/AlGaAs strained-layer SQW diode laser. A novel multiple-wavelength pump probe technique is applied which permits more comprehensive measurements than previously possible. Gain dynamics are studied for pump wavelengths in the gain, transparency, and loss regimes. In contrast to previous studies, our investigations show that free-carrier heating plays a much weaker role in determining carrier temperature dynamics than stimulated transition effects. Carrier cooling at pump wavelengths in the absorption regime is observed for the first time in these devices.

The device used for these studies is an InGaAs/AlGaAs graded-index separate-confinement heterostructure (GRINSCH) SQW ridge-waveguide diode laser[15] which is 300 μm in length with uncoated facets. The SQW has a 10-nm-thick $In_{0.13}Ga_{0.87}As$ active layer and 2.5-nm-thick GaAs bounding layers. The band gap is ~950 nm and the diode threshold current was 15 mA. Studies were performed using a multiple-wavelength pump probe technique.[14] A modelocked $Ti:Al_2O_3$ laser was coupled into an optical fiber for spectral broadening and spectral filtering was used to select temporally synchronized, independently tunable, pump and probe pulses. In strained-layer materials, the hole bands are nondegenerate at the Γ point. The pump and probe polarizations (TE) and photon energies were chosen so that only transitions from the heavy-hole band were allowed. Different frequency pump and probe photon energies simplifies the interpretation of the pump probe measurements by reducing the sensitivity to state filling at the pump wavelength. The probe wavelength may also be kept in the gain region while pumping at different wavelengths. This permits direct measurement of the change in gain produced by the pump in the gain, transparency, and loss regions. Under these conditions, a decrease (increase) in carrier temperature will result in an increase (decrease) in probe transmission.[7–13]

For our measurements, the probe wavelength was 942 nm (11 meV above the band edge) and the pump was 920 nm (43 eV above the band edge) below the energy for transitions from the light-hole band. The pulses were 120 fs with 10 nm spectral bandwidths, corresponding to a time-bandwidth product of 0.44, assuming Gaussian pulses. Measurements were performed at bias currents from 3.5 to 6 mA, below the laser threshold. Changes in bias change the gain profile so that gain, transparency, or absorption was produced at the pump wavelength. The probe wavelength was in the gain region for all cases. The carrier density in the SQW was $\sim 1\times 10^{12}/\mathrm{cm}^2$. The pulse energy inside the diode was small, ~100 and 5 fJ for the pump and the probe, respectively, so that gain changes were perturbative.

Figure 1 shows the gain dynamics for different bias currents. The instantaneous decrease in probe transmission near zero time delay in all of the traces is the result of two-photon absorption. The steplike transmission changes at long delays are produced by net changes in carrier density and depend on the position of the pump in the gain spectrum. The pump is in the gain regime for traces (a) and (b), at the transparency point for (c), and in the absorption regime for (d) and (e). Peak-to-peak transmission changes are ~1%. In order to measure relaxation

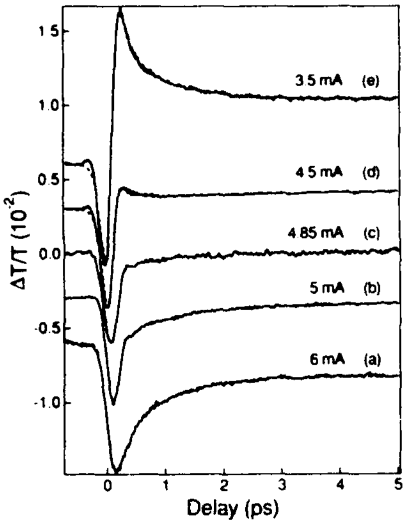

FIG. 1. Gain dynamics in InGaAs/AlGaAs strained-layer SQW diode lasers. Traces (a), (b), (c), (d), and (e) represent the experimental data for 6, 5, 4.85, 4.5, and 3.5 mA, respectively. The dashed lines superimposed on (a), (d), and (e) are the fitted curves generated for those data.

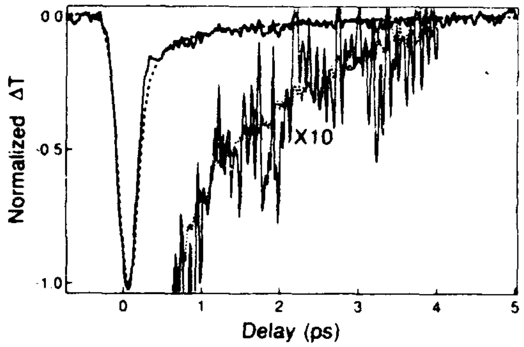

FIG. 2. Comparison of the data of trace (c) of Fig. 1 for pumping at the transparency point (solid line) with the data taken with the pump at 972 nm (below the bandgap) and the probe at 942 nm (dashed line). Ten times amplification of both traces is provided.

time constants from the data, the curves were fit by convolving exponential decays with the pulse cross-correlation[10–13] [see dashed lines on traces (a), (d), and (e) in Fig. 1].

At 6 mA bias current [Fig. 1(a)], the pump is in the gain region and stimulated transitions dominate carrier thermalization. The pump pulse removes cold carriers (carriers below the average energy) and thus heats the carrier distribution. The relaxation time of the carrier temperature is ~0.8 ps in agreement with our previous measurements.[14] At 4.85 mA of bias current [Fig. 1(c)], the pump is at the transparency point and there are no net interband stimulated transitions. In this case free-carrier absorption dominates carrier heating. To confirm this hypothesis, a complementary measurement was performed with the probe at 942 nm and the pump wavelength below the bandedge at 972 nm where only free-carrier absorption contributed to carrier heating. Figure 2 shows the measured gain dynamics and is commensurate with Fig. 1(c). The recovery time for free carrier heating is ~1.5 ps in agreement with previous measurements.[14]

At low bias currents of 3.5 mA [Fig. 1(e)], the pump wavelength is in the absorption regime. After the rapid initial decrease in transmission from two-photon absorption, the transmission increases rapidly, then relaxes. We believe that this behavior is the result of carrier cooling. The observation of carrier cooling is significant because previous studies have shown that carrier heating effects are dominant in other systems such as bulk GaAs, bulk InGaAsP, and MQW InGaAsP materials.[7-13] The only study to observe carrier cooling was the investigation of Mark *et al.*[16] in InGaAsP MQW laser amplifiers. Carrier cooling produces a transient increase in gain (or absorption saturation), rather than a transient decrease in gain (or gain saturation) that is associated with carrier heating.

Carrier cooling is produced by the generation of cold carriers at energies less than the average energy of carrier population. The average energy of carriers was calculated using a simple model where only electrons and heavy holes were considered. The calculations were calibrated by using the experimentally observed transparency photon energy. The average energy was 65 and 75 meV above the bandedge for 3.5 and 6 mA bias currents, respectively. This is commensurate with our hypothesis that pumping at 920 nm (43 meV above the band edge) generates cold carriers when the bias current is 3.5 mA and removes cold carriers when the bias current is 6 mA.

The dashed line superimposed on trace (e) of Fig. 1 shows the convolution fit to the experimental data. A decay time of ~0.8 ps is obtained for carrier cooling, which is very close to the recovery time observed for stimulated-transition-induced carrier heating. In order to fit the sharp increase and the peak of the transmission of trace (e) in Fig. 1, an exponential decay of < 100 fs (positive), has to be introduced. This fast component has also been observed in bulk AlGaAs[9] and InGaAsP MQW systems[11,12] and may be attributed to spectral hole burning effects.

Traces (b) and (d) of Fig. 1 correspond to pumping in the gain and absorption regimes close to the transparency point. For these conditions, both stimulated transitions and free-carrier absorption produced carrier temperature changes. Figure 3 shows enlargements of the data and a curve fit for 4.5 mA bias current [trace (d) of Fig. 1]. The observed dynamics result from the combination of stimulated carrier cooling and free-carrier heating. These processes have different time constants and different sign contributions. The dashed line in Fig. 3 is a fit with time constants of < 100 fs and 0.8 ps (both positive contributions), obtained from trace (e) of Fig. 1, combined with a time constant of 1.5 ps (negative contribution), obtained from trace (c) of Fig. 1. Excellent agreement is obtained with experimental data.

Our experimental observations are summarized schematically in Fig. 4. Because of the low carrier density, the average carrier energy in our experiments is higher than the transparency point photon energy. Two different effects, free-carrier absorption and interband stimulated transitions, contribute to carrier temperature changes.

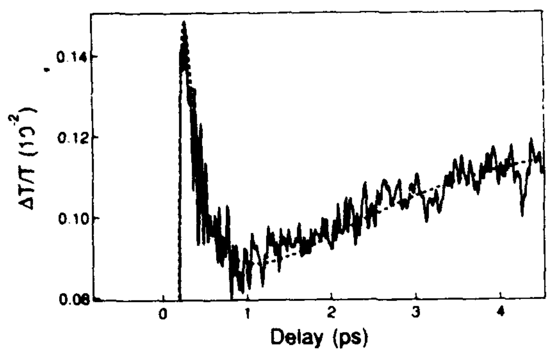

FIG. 3. Amplification of trace (d) of Fig. 1 (solid line) and its fit (dashed line).

Stimulated transitions depend strongly on the pump photon energy, while free-carrier absorption is relatively constant. For pump wavelengths near the transparency point, net stimulated carrier population changes can be strong, however, carrier temperature changes will be small. Under both of these conditions, gain dynamics will be governed by free-carrier absorption carrier heating. For pump wavelengths further from the transparency point and average energy, stimulated transition effects dominate.

In our experiments at low carrier densities, stimulated carrier cooling was observed for pump wavelengths above the transparency point (in the loss regime) and below the average energy. For high carrier densities (not shown in Fig. 4), the average energy can be lower than the transparency point. In this case stimulated carrier cooling effects may be observed in the gain regime for photon energies between the transparency point and average energy. This process would be significant because it would produce a transient increase rather than a decrease in the gain and thus enhance short pulse amplification and high speed modulation performance in these devices.

The observation of carrier cooling is only possible if free-carrier absorption heating effects are small. Our results contrast with studies in other materials systems which show that free-carrier absorption is dominant over a wide range of pump wavelengths.[7-13] This behavior may be the result of several factors, including the higher gain in a strained system and the large separation between the transparency point and the average energy for the low carrier densities used in our experiments. It is also possible that our experimental technique permits the observation of carrier cooling because measurements can be performed with pump photon energies which are well into the loss regime, while still probing in the gain regime.

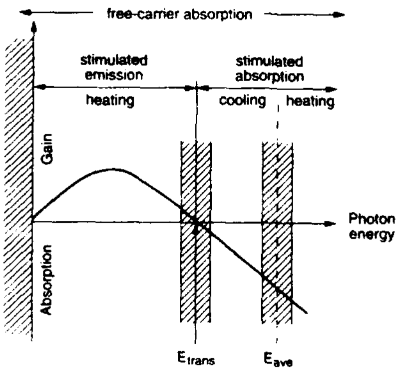

FIG. 4. Gain spectrum illustrating the regions for free-carrier heating and stimulated transition heating (cooling). Free-carrier heating dominates in the shaded area. Average energy (E_{ave}) is higher than the transparency point (E_{trans}) at low carrier density.

In conclusion, we report the first measurements of gain dynamics in InGaAs/AlGaAs strained-layer SQW diode lasers using a multiple-wavelength pump probe technique. Carrier temperature changes mediated by both free-carrier absorption and stimulated transitions were observed. Carrier cooling effects were observed for the first time in GaAs based material. An increased understanding of the physical mechanisms of gain dynamics from carrier temperature changes is important for the design of new devices. In particular, the reduction of carrier heating has important implications for reducing parasitic gain saturation effects in short-pulse modelocked laser diodes and amplifiers.

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