Phase dynamics of InAs/GaAs quantum dot semiconductor optical amplifiers

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The gain and phase dynamics of InAs/GaAs quantum dot amplifiers are studied using single and two-color heterodyne pump probe spectroscopy. The relaxation of the wetting layer carrier density is shown to have a strong effect on the phase dynamics of both ground and excited state transients, while having a much weaker effect on the gain dynamics. In addition, the dynamical alpha factor may also display a constant value after an initial transient. Such behavior is strongly encouraging for reduced pattern effect operation in high speed optical networks. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2823589]

The physics of quantum dot (QD) photonic devices has been a subject of great interest since the development of self-assembly growth techniques. One of the principle motivating factors for the study of QD lasers was the possibility of substantially reducing the phase-amplitude coupling (α factor) of semiconductor lasers from values in the region of 3–5 for quantum well devices.[1] Among the expected benefits of such a reduction were low modulation chirp, reduced filamentation in high power devices, and reduced sensitivity to optical feedback.[1] To date, QD lasers have displayed a wide range of α factors, the value displaying a strong dependence on the measurement conditions.[2,3] Recent analysis has shown that the low ground state (GS) gain saturation of QD devices coupled with a large amount of nonresonant carriers in the QD's excited states (ES) and barrier states can result in large values above threshold[4] and as a consequence, directly phase modulated devices have been demonstrated.[5] In addition, it has been proposed that the unique carrier dynamics of QD semiconductor optical amplifiers (SOAs) would lead to a reduction of patterning effects compared to conventional devices, for both linear and nonlinear applications.[6,7] As the understanding of relevant carrier relaxation processes in QD structures improves, additional device functionalities will be realized.

Heterodyne pump probe spectroscopy has been established as an ideal tool to directly record the ultrafast gain and refractive index dynamics of SOA devices. Previous studies of the gain and phase dynamics of QD SOAs have been performed by Borri *et al.*, who investigated the effects of carrier heating and spectral hole burning in InAs/InGaAs QDs,[8] while related techniques have been used to measure the α factor in various conditions.[9] Previously on InAs/GaAs QDs, we demonstrated the importance of Auger-mediated carrier capture using a single color pump probe technique[10] and illustrated the effects of ultrafast hole relaxation on the gain recovery[11] using a two-color technique. In this letter, we report on two-color phase measurements of the same structure, and note the presence of a strong phase recovery component at the same time scale as the wetting layer carrier recovery. In addition, we combine these phase measurements with two-color gain measurements to calculate an α factor for the device as a function of pump probe delay. The experimental arrangement is similar to that reported in Ref. 11. Calibrated phase changes are obtained using a scheme similar to Ref. 12, where a high frequency lock-in is used to directly measure the phase at the heterodyne frequency. See Ref. 10 for further details on the SOA and InAs based QD material system.

Figure 1 displays the gain as a function of device bias current for GS and ES. The GS gain (solid line) exhibits the onset of saturation above currents of 40 mA and GS and ES gains are equal at currents around 100 mA. Figure 2 displays the phase and gain recovery of the SOA biased at 100 mA where both GS and ES energies exhibit similar gain. As was the case in Ref. 11, in general, the gain recovery can fitted by a triexponential function, with a short time ($\sim$1 ps) associated with hole redistribution and ES to GS carrier relaxation, an intermediate time (1–10 ps) associated with electron capture to the dot and electron escape from GS to ES and a long time $>$100 ps associated with the recovery of the wetting layer. However, in the phase case, the response can be represented by a biexponential function with a shorter time (2–5 ps), which we associate with processes linked to the

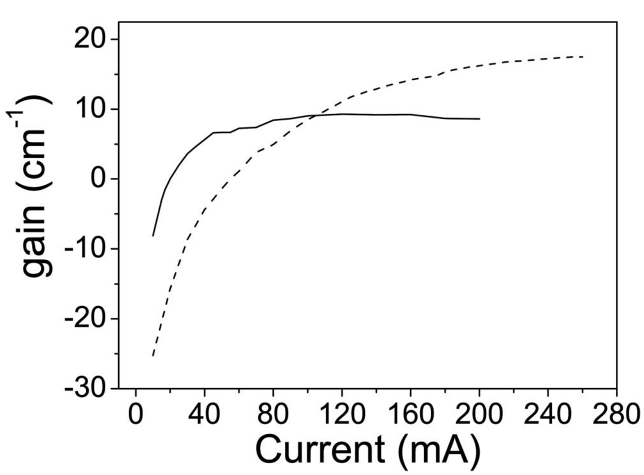

FIG. 1. GS (solid curve) and ES (dashed curve) gains as a function of current. GS transparency occurs at 15 mA, ES transparency occurs at 55 mA. Gains are equal around 100 mA.

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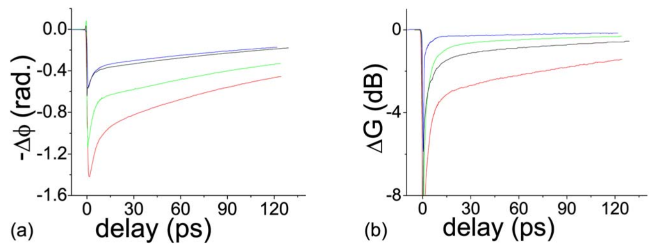

FIG. 2. (Color online) Recovery dynamics of (a) the phase and (b) the gain observed at 100 mA: (blue) ES pump GS probe, (green) GS pump GS probe, (black) ES pump ES probe, and (red) GS pump ES probe.

two shorter times in the gain case, and a longer time (>100 ps), which we associate with the long time in the gain case.

Interestingly, comparison between gain and phase recoveries of either state reveals a much stronger long time component in the phase case, strongly suggesting the importance of the wetting layer recovery on the phase dynamics. An additional feature of the phase dynamics is the close correspondence between the ES pump, ES probe case (black) and the ES pump, GS probe case (blue). The close correspondence between these two cases indicates that a perturbation at the ES energy results in very similar phase recoveries of both GS and ES. In the case of perturbation at the GS energy, the ES experiences a larger initial phase change than the GS.

To further investigate these features, the recovery at an increased injection of 180 mA is displayed on Fig. 3. In general, each of the four transients exhibits a larger instantaneous reduction in phase when operating at higher injection. Comparison between the gain and phase recoveries confirms that the phase dynamics contains a much stronger, long time component than the corresponding gain dynamics. Also, the correspondence between the GS and ES phase recoveries remains, when pumped at the ES (blue and back curves). Another point to note is that the overall difference between the different phase recoveries has reduced at higher currents, similar to the trend in the gain transients.

It is worthwhile to consider the effective or dynamical α factors [here termed $\alpha_d(t)$], in order to gain additional understanding of the QD SOA and its possible applications. It is calculated using the relation

$$\alpha_d(t) = -\frac{4\pi}{\lambda}\frac{\Delta n(t)}{\Delta g(t)},$$

where $\Delta n(t)$ and $\Delta g(t)$ are the pump induced refractive index and gain transients as a function of time. An alternative definition based on the derivatives of the refractive index and gain responses could also be used (see, e.g., Ref. 13) and leads to very similar results.

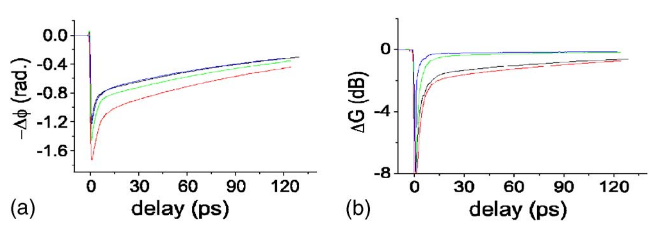

FIG. 3. (Color online) Recovery dynamics of (a) the phase and (b) the gain observed at 180 mA: (blue) ES pump GS probe, (green) GS pump GS probe, (black) ES pump ES probe, and (red) GS pump ES probe.

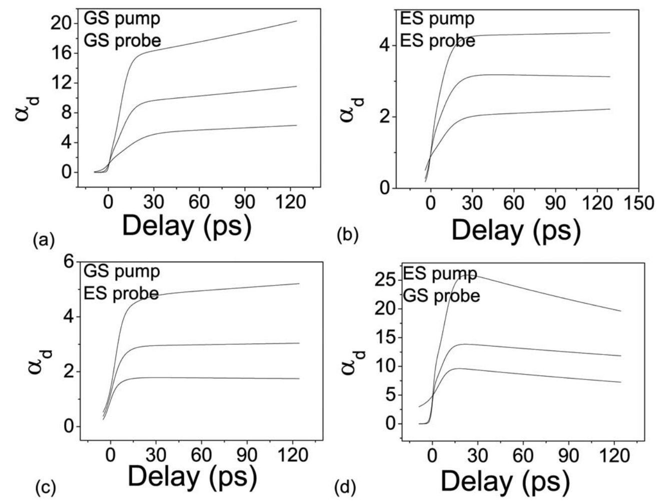

FIG. 4. $\alpha_d(t)$, calculated from the tri-/biexponential fits to the gain/phase data at currents of 70, 120, and 180 mA [$\alpha_d(t)$ increasing with current]: (a) GS pump GS probe, (b) ES pump ES probe, (c) GS pump ES probe, and (d) ES pump GS probe.

Figure 4 displays $\alpha_d(t)$ for each of the four GS, ES pump/probe possibilities at various currents. To reduce the noise, $\alpha_d(t)$ is calculated from the tri-/biexponential fitted functions rather than directly from the experimental data. In many cases, it is evident that $\alpha_d(t)$ approaches a constant value (when pumped at either GS or ES) after an initial transient whose duration depends on injection level. This indicates that both gain and phase exhibit the same time dependence for times longer than $\simeq$20 ps. Such behavior is very similar to that already predicted in Ref. 9 using a complicated mesoscopic model. The cases where α_d increases/decreases for long times may be understood when one considers the amplitude of the long time component of the gain recovery. The low value of this component results in increased uncertainty in the measurement of its slope (see gain transients in Figs. 2 and 3). As the injection level increases, the initial transient duration reduces due to the increased population in the dot.

The evolution of the dynamical alpha factor to a constant value indicates the similarity of long time evolutions of both gain and phase responses. This strongly suggests that the dominant contribution to the phase response for long times is the same as in the gain case, i.e., due to the recovery of the wetting layer population. This conclusion is in agreement with a previous theoretical study which computed the phase contributions from a variety of QD carrier processes and concluded that the contribution from the wetting layer would dominate in the regime of maximal gain.[7] An important consequence of this feature was the prediction of pattern-effect-free cross phase modulation. Our experimental evidence supports the main theoretical findings of this report and thus provides a strong case for the reduced pattern effects predicted.

In order to understand and predict the shorter time scale observed in the phase dynamics (i.e., 3–5 ps), and the behavior of the phase transients in more detail, it is necessary to perform a quantitative analysis of the various carrier relaxation processes. This analysis should include the effects of inhomogeneous broadening due to dot size dispersion and pump probe nonlinearities which may also contribute, such as two-photon absorption. These calculations will be the subject of a future publication.

In conclusion, we have presented two-color heterodyne pump probe measurements of the ultrafast gain and phase transients in QD SOA structures. Our experimental results strongly suggest that the recovery of the wetting layer carrier density becomes the dominant phase contribution at high carrier densities. This observation is in agreement with the calculations performed in Ref. 7 and is encouraging for the realization of nonlinear devices exhibiting lower pattern effects than conventional SOAs.

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