Ultrafast Gain and Refractive Index Dynamics in AlInAs/AlGaAs Quantum Dot Based Semiconductor Optical Amplifiers Operating at 800 nm

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***Abstract*—The ultrafast gain and refractive index dynamics in AlInAs/AlGaAs quantum dot (QD) based semiconductor optical amplifiers is reported. Measurements in the forward bias regime indicate a complete gain recovery timescale of ∼5 ps, while the phase dynamics occur over a much longer timescale. At increased pump powers, the impact of nonresonant carriers created by two-photon absorption is visible as an increased injection in both gain and phase dynamics. Reverse-biased measurements reveal a similar behavior to previous measurements on InAs QD devices.**

***Index Terms*—Optical amplifiers, optical materials, semiconductor device measurements.**

I. Introduction

SEMICONDUCTOR quantum dots have potentially very interesting properties for use as a nonlinear optical material due to the 3D confinement of charge carriers that results in unique properties not achievable with conventional material systems. They are often considered as a solid-state analog of atoms. Although this picture has proven to be very naive for single quantum dots [1], it is likely that some key nonlinear optical properties will survive for larger QD densities. For instance, enhanced four wave mixing efficiency has been reported in the InAs/GaAs quantum dots [2] and InAs/InP quantum dot/dash material systems [3]. In particular, this has enabled short pulse generation from single section Fabry-Perot lasers [4]. One interesting property of quantum dots is that it may be possible to tune the sign of the nonlinear index of refraction i.e. they can exhibit both focusing and defocusing nonlinearities [5]. This property cannot be found in other passive bulk materials or in quantum wells. Another interesting property is that their nonlinear absorption can be saturated at low intensity with fast dynamics [6]. Hence, they can be used as saturable absorbers to fabricate high-speed sources such as mode-locked lasers [7]–[9]. Finally, in contrast to other semiconductor materials (bulk or quantum wells), a noticeable immunity of the physical properties to heat is expected for quantum dots. This is especially interesting in the context of nonlinear optics since the system must be driven at quite a high intensity for nonlinearities to appear. AlInAs/AlGaAs quantum dots are promising new quantum-dot materials emitting in the 750–850 nm range [10], [11], for both fundamental physics or applications such as photodynamic therapy. While they emit in the near-infrared (NIR) range where a lot of high-power and low-cost sources exist, this material system offers the distinct advantage of providing temperature insensitive operation. This is because the emission states are deep states not affected by thermal escape or other carrier escape mechanisms.

For the targeted applications, it is especially important to understand the ultra-fast gain and refractive index dynamics. Previous studies dealt with the non linear gain dynamics of InAs(Ga)/GaAs QD amplifiers operating beyond 0.9 μm [12]–[14]. It was shown in particular that at least three non linear processes take place in InAs/GaAs QDs operating at 1150 nm corresponding to carrier relaxation to the ground state, phonon scattering and carrier capture from the wetting layer [12]. Also, the linewidth enhancement factor (LEF) which is a fundamental parameter that determines the performance of semiconductor lasers and amplifiers was studied by means of pump probe experiments in InGaAs/GaAs QD amplifiers operating at 0.92 μm [14]. It was shown that the LEF amounts to about 1 at the dot GS transition and generally increases with increasing carrier density [14]. However, no detailed experimental investigation of the carrier dynamics of AlInAs/AlGaAs QD material system has ever been reported. In this paper, we experimentally analyse the optical response of this material system whose physical properties are not very well established yet. We report for the first time, the measurement of the gain and refractive index dynamics in AlInAs/AlGaAs QD based waveguides operating at 800 nm. Applications in self-organization in optical systems and in

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laser mode-locking are expected [15], [16]. For both of these applications, the properties of interest are the steady-state and transient characteristics of the nonlinear susceptibility, and in particular the nonlinear index of refraction and nonlinear absorption. The measurements are performed on single-mode ridge waveguides that can be injected with an electrical current. We measure the ultra-fast dynamics of the system using single-color pump probe spectroscopy and provide evidence of a fast gain recovery of the system of the order of 5ps.

In section II of the paper, we detail the structure of the samples under investigation (sec. II-A) and present their basic optical characterization under current injection (sec. II-B). In sec. II-C, the pump-probe technique used to record the gain and phase dynamics is described. Experimental results obtained in various regimes and current injection conditions are presented in sec. III. Finally, the results are discussed and we conclude in section IV.

II. Sample Design, Characterization and Experimental Set-Up

A. Sample Design

The layer structure was designed to achieve transverse single mode waveguide and optimized in terms of optical confinement factor using a beam propogation algorithm. The structure is composed of a planar waveguide with 5 layers of $In_{0.8}Al_{0.2}As/Al_{0.2}Ga_{0.8}As$ QDs inserted in a lower index $Al_{0.86}Ga_{0.14}As$ layer (1.5 μm). The waveguide thickness is 250 nm (1-lambda at 800 nm). Beam propagation modelling showed that etching a 2 μm wide ridge waveguide yields optical confinement factors of 77%, 22%, and less than 0.01% in the core, cladding, and GaAs regions respectively. These values preclude unintended absorption of the mode in the GaAs substrate. The core waveguide consisted of the growth of 5 sequences of 41.7 nm-thick $Al_{0.2}Ga_{0.8}As$ followed by a QD layer formed by deposition of 3.54 monolayers of $In_{0.8}Al_{0.2}As$, and finally a sixth 41.7 nm-thick $Al_{0.2}Ga_{0.8}As$ layer. The QDs were grown by MBE with the standard Stransky-Krastanov growth mode. A cap layer of highly-doped GaAs (p-doped, 200 nm thickness) was deposited for the upper gold contact. Broad area lasers were processed from the layer structure and ground state emission was observed at 775 nm at room temperature in a pulsed regime for cavities as short as 545 μm. The as-grown structure was further processed into narrow ridge single mode waveguides (2 μm-width). Specific attention was paid to the etch depth. Using in-situ control by means of interferometry, the upper cladding layer was almost completely etched in order to achieve a single mode waveguide and optimized optical confinement factors. The waveguides were tilted with a 7 degree angle to minimize back reflection. Both facets were ascleaved.

B. Amplified Spontaneous Emission

Figure 1(a) displays the amplified spontaneous emission (ASE) properties of the device as a function of injection to twice the transparency level (estimated to be 15 mA). At each injection the shape could be fitted with a single Gaussian, whose width varied by 10% over the range of injection

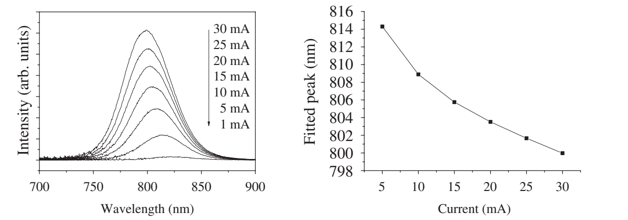

Fig. 1. (a) Amplified Spontaneous Emission (ASE). (b) Peak emission (ASE) as a function of current.

levels. We associate this peak with the inhomogeneously broadened ground state (GS) of the QD ensemble and note that no evidence of saturation of the peak occurred over the range of injection currents used. No emission corresponding to the QD's Excited State (ES) was detected. The peak of the ASE exhibits a blue shift as the current increased, as shown on Figure 1(b). Its sub-linear dependence on current is possibly due to the onset of a compensating thermal redshift at increasing currents.

A similar blueshift has been seen in the below threshold, Hakki-Paoli gain spectra of InAs based QDs [18]. Such a blue shift can be understood in terms of the dependence of the carrier capture and escape processes for QDs of different sizes.

It should be first noted that at room temperature, the capture time depends marginally on the QDs' size for both deep and shallow QDs. In contrast, the escape time depends on the energy barrier height and is shorter for shallow QDs (higher transition energy) than for deep ones (smaller transition energy). At a given current injection, carriers are injected almost equally in deep and shallow QDs. As a consequence of the different escape times, a statistical redistribution of the QDs population occurs and deeper QDs tend to be more populated. As the injection is increased, GS saturation affects the longer wavelength dots first and the population redistributes because of Pauli blocking among the available sites, i.e. towards shallower dots with higher transition energies, resulting in a blue shift in the ASE spectrum.

C. Pump-Probe Technique

The ultrafast dynamics were measured using a single color pump probe technique with heterodyne detection similar to that described in [19]. Briefly, pulses of duration shorter than 200 fs (80 MHz repetition rate) are obtained from a Coherent Chameleon ultrafast laser and split into three beams: reference, pump, and probe. After propagation through the SOA waveguide with suitable delays, the frequency shifted probe and reference beams are overlapped on a detector, and the amplitude of the difference frequency is detected using a high frequency lock-in amplifier. The resulting signal is proportional to the differential transmission ΔT of a probe pulse at the same wavelength as the pump. The resulting data are represented as the gain change ΔG by the formula $\Delta G = 10log(\Delta T/T_0)$ where T_0 is the transmission without pump beam. Measurements are taken at room temperature and performed both as a function of forward bias current and reverse bias voltage.

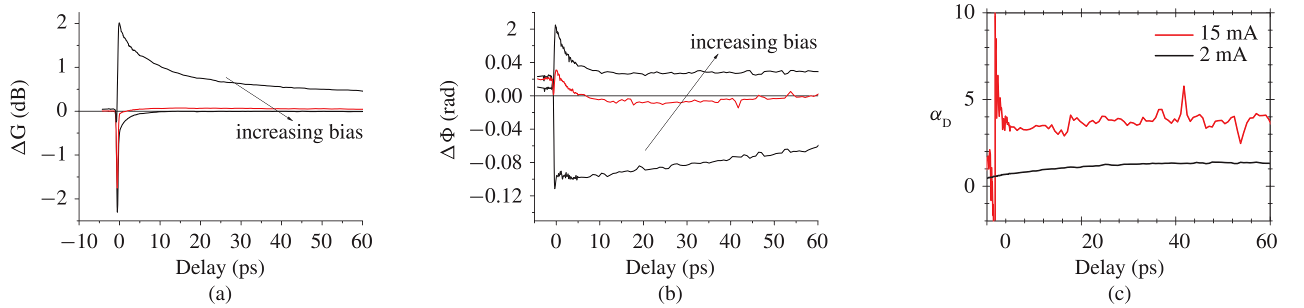

Fig. 2. Gain (a), phase (b) and alpha-factor (c) dynamics following the injection of pump pulse of average power 0.5 mW. The transparency case is shown in red and measurements were also taken at 2 mA and 30 mA.

III. Results - Gain and Phase Dynamics

A. Low Pump Power

Pump-probe gain and phase dynamics are shown in Figures 2(a) and 2(b) respectively, at various injection levels for an average pump power of 0.5 mW (pump energy of ∼6 pJ, transparency case shown in red) and correspond to pump/probe wavelengths of 800 nm.

Below transparency, the pump pulse causes an instantaneous increase in the amplifier transmission due to the absorption of part of the pump pulse. The signal then recovers towards its unperturbed value. The recovery can be fitted with a bi-exponential function, resulting in characteristic relaxation times of ∼6 ps and ∼100 ps. In contrast, the corresponding phase dynamics shows an approximately linear recovery behaviour, as shown in Figure 2(b). The resulting dynamical alpha-factor is calculated from the dynamical phase and gain changes (see [21] for details of calculation). As shown in Figure 2(c), it eventually reaches a constant value indicating that, although their behaviours are quite different in the initial stages, the gain and phase dynamics recover at the same rate in the long time limit and are therefore connected to the same carrier process i.e. interband recombination. The value reached in the long time limit (∼1.2) is similar to that measured for InAs quantum dot lasers using sub-threshold ASE techniques [17], [18].

At transparency (red lines, Figure 2) the gain shows an instantaneous reduction and recovery due to both coherent/incoherent artifacts [20]. In addition, there is an overshoot of the $\Delta G = 0$ line which occurs at ∼2 ps which then decays slowly over time. The corresponding phase dynamics undergoes a slower transient before also crossing the $\Delta\phi = 0$ line at ∼5 ps and recovering in a similar fashion. Again, the corresponding dynamical alpha factor is constant at a value of ∼4 once the initial overshoot occurs, indicating that the gain and phase dynamics are eventually connected to the same carrier process.

At twice transparency, the gain shows a greater instantaneous decrease (when compared with the transparency case) due to instantaneous carrier depletion induced by the pump pulse, before recovering to its unperturbed level. This recovery can be fitted by a bi-exponential function with characteristic times of ∼1.5 ps and ∼5 ps. These recovery times are broadly similar to those measured for the InAs/GaAs QD system at 1.3 μm with an important difference. The gain of the system has fully recovered within 10ps while in the InAs/GaAs case, a third time connected with dot re-filling processes is present [21]. Thus, the limiting gain timescale of this device is ∼10 ps. After an initial increase due to the removal of carriers, the corresponding phase also exhibits a fast recovery ∼10 ps, which is associated with the gain recovery. However, unlike the gain, the recovery contains an additional long timescale and takes 100’s of picoseconds to recover completely to its initial value.

The presence of an overshoot in both the phase and gain at transparency may indicate some delayed pumping mechanism due to non-linearities in the device. For example, additional pumping due to two photon absorption (TPA) [22] or bound-to-continuum absorption (BCA) [23] has been previously suggested for QD structures and would result in pump-induced carrier populations in barrier levels that can be subsequently re-captured to the dot after some time. Such an effect should depend on pump power and we will investigate this point in the next section.

B. Increased Pump Power

The results outlined in this section were recorded for a pump power of 1 mW. Figure 3 displays transient gain and phase dynamics, measured at a variety of currents (transparency in red) and the calculated dynamical alpha factors below and at transparency to compare with the previous section. The gain dynamics are similar to those recorded at lower pump power except the presence of an increased overshoot which is additionally present above transparency. The phase dynamics display greater changes due to the increased pump power. The initial phase offsets due to the pump pulse are similar to those measured in the previous section i.e. negative below transparency and positive above transparency. However, after the initial perturbation, each phase transient contains a component that gradually reduces the phase over the first 10 ps. Beyond this, each phase transient then recovers towards zero with a similar timescale. The corresponding dynamical alpha-factors at lowest injection and transparency levels have also increased, as shown on figure 3(c).

The increased overshoot in the gain and gradual reduction of the phase over the first 10 ps are consistent with an additional pumping mechanism at increased pump powers due to either BCA or TPA. Such processes result in additional carriers being

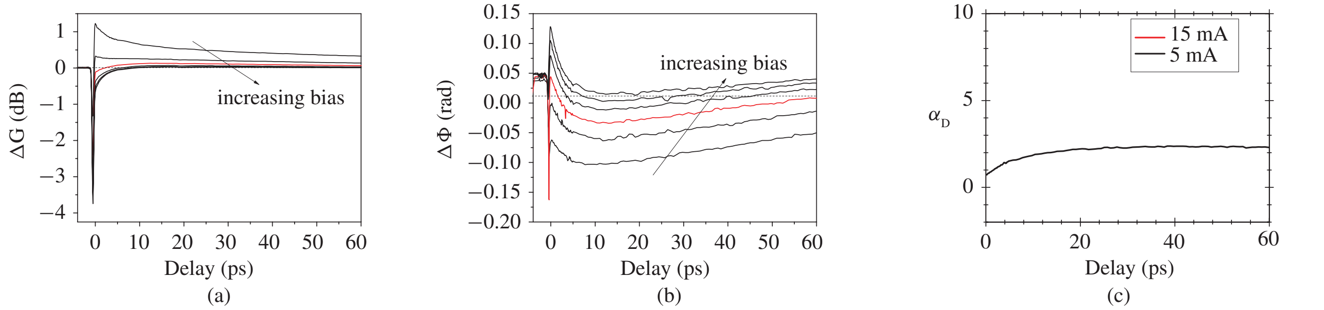

Fig. 3. Gain (a), phase (b) and alpha-factor (c) dynamics following the injection of pump pulse of average power 1 mW. The transparency case is shown in red and measurements were taken up to twice transparency (from 2 mA to 30 mA).

promoted to high lying barrier layers from where they gradually relax into adjacent layers and eventually the dots. As the phase change includes contributions from carrier populations in adjacent layers (due to the the Kramers-Kronig relations), the gradual carrier buildup in the dot and adjacent layers over the first 10 ps results in a gradual phase reduction, present at all injection levels. The dot population is also affected by these changes through changes in the capture/escape rates. However, the resulting effect on the gain is not as dramatic. This process also results in a larger dynamical alpha factor as seen in Figure 3(c).

C. Effect of Detuning

In order to investigate the effect of detuning on the gain and phase recovery dynamics, the same kind of measurements were performed on either side of the ASE peak (at ∼800 nm) and at a 1 mW pump power. Figures 4(a) and 4(b) show the shorter wavelength (775 nm) gain and phase dynamics respectively while Figures 4(c) and 4(d) show the longer wavelength (825 nm) gain and phase dynamics respectively.

For the 775 nm case, the transmission of the device is always increased by the pump and thus is absorbing over the range of currents used. In the corresponding phase dynamics, a similar behaviour to that seen in Figure 2(a) (lowest injection case) is observed at most injections with some transient pumping type behaviour occurring for the highest two injection levels. This behaviour of the phase dynamics is consistent with the large absorption visible in the transmission which depletes the pump pulse and thereby minimises non-linear processes such as TPA or BCA.

For the 825 nm case, the opposite situation is present. When the pump pulse arrives, Figure 4(c) indicates that, apart from a weak signature at the lowest injection, we do not observe an increase of the transmission at any injection level and so the waveguide is always above or very close to transparency at this wavelength. In the above transparency cases, the gain recovery dynamics is very similar to the cases in the previous section where the gain depletion quickly recovers and we observe an over-shoot at ∼10 ps. The corresponding phase dynamics is shown in Figure 4(d). After the pump induced phase increase due to depleted carriers (present at all but the lowest injection case), a gradual decrease in the phase occurs over ∼10 ps before it again increases towards the unperturbed level. This phase behaviour is very similar to that

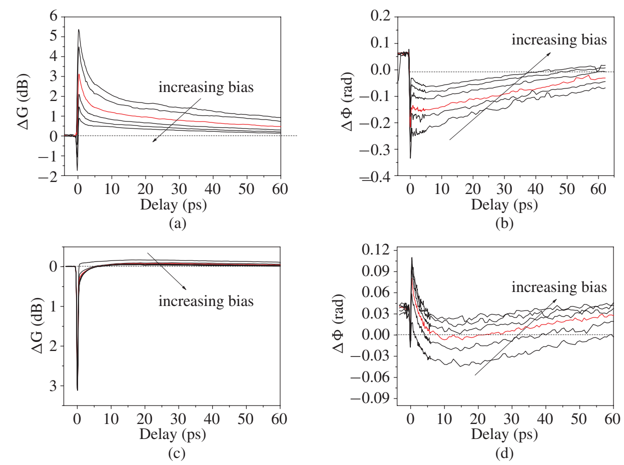

Fig. 4. Detuned pump probe measurements at 775 nm for (a) gain and (b) phase and at 825 nm for (c) gain and (d) phase. The average pump power was 1 mW, the case corresponding to transparency at 800 mn is shown in red and measurements were taken up to twice this level (from 2 mA to 30 mA).

in Figure 3(b) (highest injection) and the gradual decrease over 10 ps can be again attributed to transient pumping due to TPA or BCA. The effect is more pronounced at this wavelength due to the reduced interband absorption (as seen in the gain transients) which preserves the energy of the pump pulse for stronger TPA or BCA processes.

To further investigate the nature of the non-linear transient pumping effect that results in a gradual decrease in phase over the first 10 ps (for high pump power cases), we further detuned the pump-probe wavelength by 25 nm to 850 nm and examined the effect of varying the pump at different injection levels. The corresponding gain transients are shown in Figure 5(a) for pump powers of 1 mW (black) and 3 mW (red) at injection levels of 2 mA and 30 mA. As the wavelength is much longer than the ASE wavelength range, we do not expect the pump pulse to induce interband effects. As shown in Figure 5(a), this is the case, and the very fast gain dynamics (which follows the original laser pulse's auto-correlation) are only present when pump and probe pulses overlap and so are due to non-linear absorption effects such as TPA, possibly combined with coherent effects such as four wave mixing. As is apparent from the graph, increasing the injection has much less impact on the transients than increasing the pump energy. In Figure 5(b), the corresponding phase dynamics is presented. Again, changes

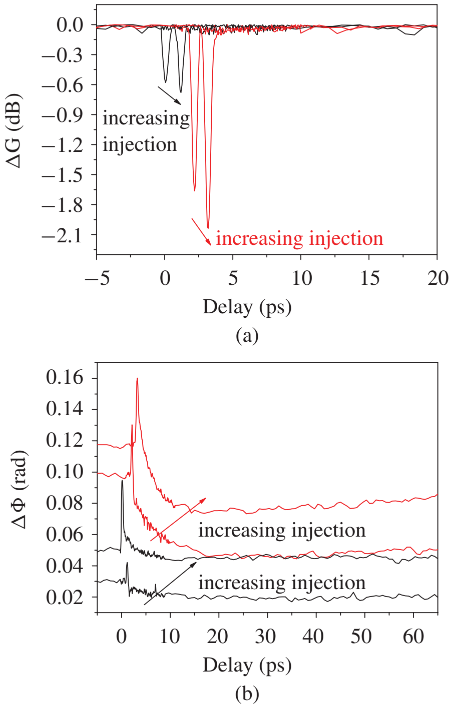

Fig. 5. Pump probe measurements at 850 nm at average pump powers of 1 mW (black) and 3 mW (red) for injection levels of 2 mA and 30 mA. (a) Gain data (offset horizontally for clarity) (b) Phase data (offset vertically for clarity).

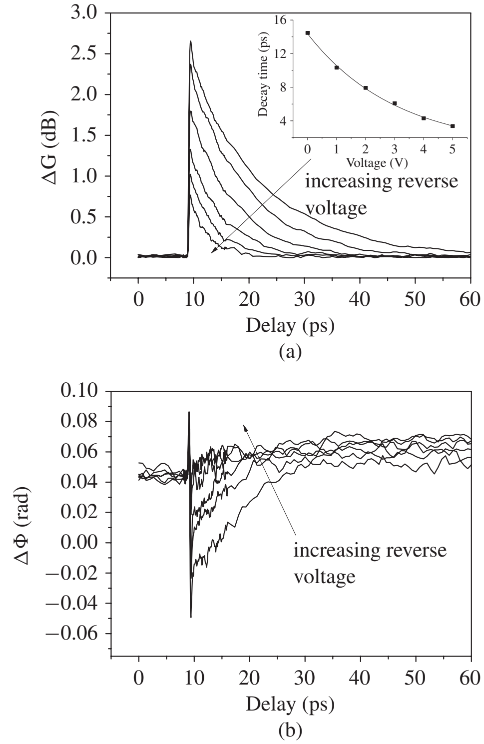

Fig. 6. Gain (a) and phase (b) dynamics in reverse bias mode 800 nm. The reverse voltage range was 0−5 V and pump power was 1 mW. The inset shows the dependence of the single exponential recovery time on voltage.

due to increased pump power are much more pronounced than changes due to increased injection. The characteristic phase decrease over the first 10 ps is equally present at both injection levels for increased pump power, while it is barely visible at lower pump power. Thus, this behaviour is largely independent of the dot population and pump power is the most important factor suggesting TPA as the most likely cause. BCA should depend on the dot population and would not appear to play a strong role.

D. Reverse Bias

To investigate the suitability of this material system for active absorber applications, a reverse bias was applied to the device and transmission and phase dynamics were recorded. The results are displayed in Figure 6. The recorded dynamics are very similar to the InAs/GaAs dot case for both the absorption [6] and phase [5] dynamics. In the case of the absorption dynamics, shown in Figure 6(a), the initial pump induced absorption bleaching decreases as the reverse bias increases due to the corresponding increase of spatial separation of QD electron and hole wavefunctions [24]. The absorption recovery in this voltage range is primarily due to thermionic emission from the dot [6]. As the reverse bias voltage is increased, the effective barrier height reduces and thus the absorption recovers more quickly. The recovery time τ_R can be extracted from a single exponential fitting and its voltage dependence is described by the expression $\tau_R = \tau_{R0}\exp(-V/V_0)$ with $\tau_{R0} = 14$ ps and $V_0 = -3V$ (see Figure 6(inset)) . In InAs based dots, the corresponding values are $\tau_{R0} = 18$ ps and $V_0 = -2V$ [25]. As shown in Figure 6(b), the phase changes due to this process are very small and diminish as the reverse bias increases. A similar behaviour was reported in [5] at the peak of the absorption spectrum and attributed to cancelling effects from positively and negatively detuned dots, each of which exhibits atom-like dispersion.

IV. Discussion and Conclusion

The ultrafast gain and refractive index dynamics in AlInAs/AlGaAs quantum dot based semiconductor optical amplifiers operating at ∼800 nm is reported, to our knowledge for the first time. The amplified spontaneous emission displayed a blueshift with increasing injection, similar to previous reports for laser structures [18] and is explained in terms of the capture and escape dynamics that occur for different sized dots at room temperature. Pump probe measurements in the forward biased regime indicate a complete gain recovery timescale of ∼5 ps, while the phase dynamics occur over a much longer timescale. To further investigate the appearance of an overshoot in both gain and phase dynamics at transparency, measurements at increased pump were performed. Here, the impact of nonresonant carriers created by two photon absorption was visible as an increased injection in both gain and phase dynamics both on resonance and at detuned wavelengths, a process suggested theoretically in Ref. [22]. Reverse biased measurements reveal a similar behaviour to previous measurements on InAs quantum dot devices [25]. The experimental results shown here will prove useful in clarifying the potential applicative fields of AlInAs/AlGaAs QDs. The very fast gain recovery dynamics measured here suggests that this material system could be exploited for ultra-short pulse generation in mode-locked lasers in the visible range.

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