Ultrafast Gain and Index Dynamics in an InAs/InGaAsP Quantum Dot Amplifier operating at 1.55 µm

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Abstract: The gain and index dynamics of a QD amplifier operating at 1.55 µm are characterized via heterodyne pump-probe measurements with 150 fs resolution. A 13 ps gain recovery time was found, promising for all-optical signal processing.

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1. Introduction

Self-assembled quantum dot (QD) Semiconductor Optical Amplifiers (SOAs) are currently attracting attention for all-optical signal processing applications because they have significantly faster carrier recovery times compared to conventional multiple quantum well, or bulk SOAs [1]. However previously studied QD lasers and amplifiers based on the GaAs material system have operated only in the 1.1-1.3 µm wavelength range, not in the 1.55 µm wavelength range needed to make them practical for telecommunications. In this work we report the first heterodyne pump-probe characterization of the ultrafast gain and index dynamics of an InAs/InGaAsP self-assembled QD SOA with its peak gain in the important 1.55 µm telecommunications wavelength range.

2. Sample and Experiment

The QD amplifier measured is a 1.55 µm InAs/InGaAsP laser diode from those reported in [2], with the end-facets anti-reflection coated to suppress lasing to create a single-pass amplifier. The diode structure is a p-i-n doped ridge-waveguide grown by chemical beam epitaxy on an InP substrate, cleaved into 1-mm length bars. Its undoped 400 nm thick core region consists of five stacked layers of self-assembled (SK-grown) InAs dots grown in $In_{0.816}Ga_{0.184}As_{0.392}P_{0.608}$, creating 3.1% lattice strain for InAs dot growth, and providing a high energy barrier for the QDs.

The temporal dynamics of the sample were measured using a heterodyne pump-probe experiment, as described in [3], and based on that described in [4,5]. The laser source was a Ti:sapphire pumped optical parametric oscillator (OPO), providing 150 fs pulses at a repetition rate of 76 MHz. The setup allows for simultaneous measurement of both amplitude and phase dynamics, at any wavelength within the tuanable range of the OPO laser, and any polarization. For these measurements the wavelength was set to 1550 nm, near the gain peak of SOA, and the polarization was maintained in the TE state.

3. Experiment Results

The heterodyne pump-probe measurements performed reveal the dynamics of both the long-lived carrier density changes, and the short-lived dynamics attributed to two-photon absorption (TPA) and carrier heating (CH). The long-lived dynamics shown in Fig. 1 (a) measured over the full pump delay translation range of 4 ns clearly show the carrier-recovery lifetime τ_{cr} in the absorption regime (5-25 mA), and the gain-recovery lifetime τ_{gr} in the gain regime (50 mA, inset of Fig. 1 (a)). The traces fit well to single exponential decays (dotted lines in the figure), with lifetimes of $\tau_{cr} \approx 500$ ps, and $\tau_{gr} = 13$ ps. These lifetimes are similar to those previously observed in highly-confined InAs/AlGaAs QDs in [4], leading to the conclusion that the carrier-recovery time in the absorption regime corresponds to the spontaneous carrier recombination time for the QD ground state, and the gain recovery time corresponds to the rate of refilling of the carriers to the dot ground state via phonon-assisted relaxation. Furthermore the similarity of these recovery times to the highly-confined InAs/AlGaAs QDs reinforces that high quantum confinement has also been achieved in our InAs/InGaAsP dots.

The short-lived dynamics shown in Fig. 1 (b) reveal the ultrafast dynamics around zero delay and clearly show two-photon-absorption (TPA) and carrier heating (CH) dynamics as expected from previous studies in QD and quantum-well (QW) SOAs. Thus the CH dynamics can be fitted to a phenomenological model involving a bi-

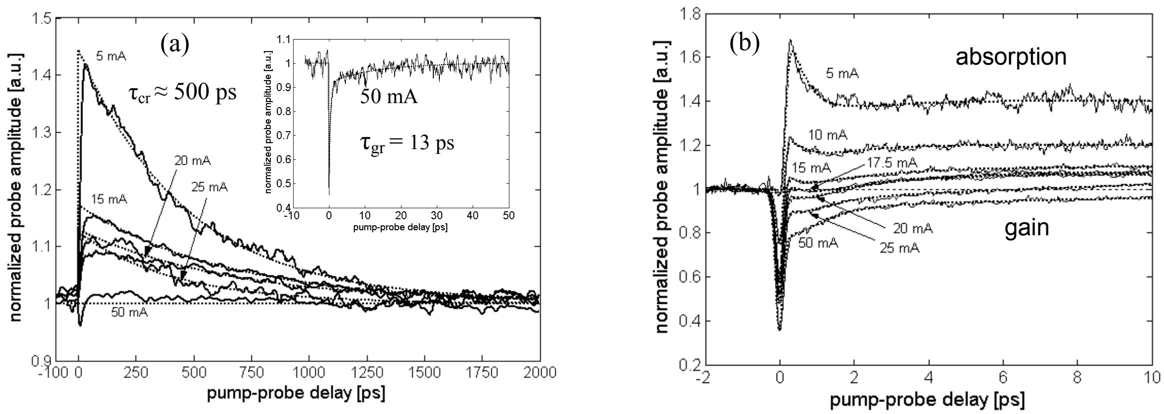

Figure 1 – Long-lived (a) and short-lived (b) gain dynamics measured from the 1.55 µm QD SOA versus bias current. Dotted lines show exponential fits. The inset in (a) shows a magnification of the 50 mA trace from 0 to 50 ps.

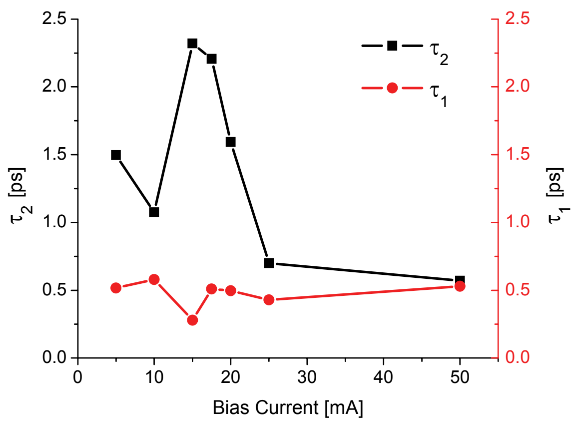

Figure 2 – Values of the time constants of the exponential fits to the short-lived curves in Fig. 1 (b) v.s. bias current.

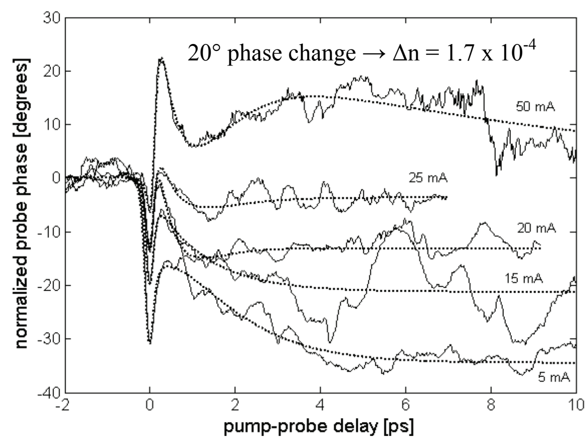

Figure 3 – phase dynamics versus bias current measured simultaneously with amplitude dynamics

exponential function $h_{ch} = k_1 e^{-t/\tau 1} - k_2 e^{-t/\tau 2}$. Good fits to all of the short-lived traces measured were obtained using this model, and values of $\tau_1 \approx 0.5$ ps and $\tau_2 \approx 0.5$ - 2.5 ps were found for the CH lifetimes were obtained. Values found for the time-constants versus bias current are shown in Fig. 2. We also note that strong carrier heating features observed here are in contrast to the those reported for the QD SOAs in [6], which showed carrier heating responses with similar lifetimes, but significantly reduced in magnitude. In [6] the reduction in carrier heating was attributed to a reduction in free carrier absorption (FCA), thus stronger CH here suggesting FCA is more prominent in our QD SOAs. Fig. 3 shows the short-lived phase dynamics measured simultaneously with the amplitude dynamics. Good fits (dotted lines) to the curves were obtained using the same exponential model as for the amplitude dynamics, giving values of 0.5 - 1.5 ps for τ_1 and τ_2 from the phase measurements as found in the amplitude dynamics.

4. Conclusion

We have reported the first systematic study of the ultrafast gain and index dynamics of a 1.55 µm quantum dot SOA, finding a gain recovery time of 13 ps, making the device promising for ultrafast signal processing at ~100 GHz, and CH dynamics with lifetimes of 0.5 - 2.5 ps.

5. References

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