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Complex characterization of short-pulse propagation through InAs/InP quantum-dash optical amplifiers: from the quasi-linear to the two-photon-dominated regime

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Abstract: We describe direct measurements at a high temporal resolution of the changes experienced by the phase and amplitude of an ultra-short pulse upon propagation through an inhomogenously broadened semiconductor nanostructured optical gain medium. Using a cross frequency-resolved optical gating technique, we analyze 150 fs-wide pulses propagating along an InP based quantum dash optical amplifier in both the quasi-linear and saturated regimes. For very large electrical and optical excitations, a second, trailing peak is generated and enhanced by a unique two-photon-induced amplification process.

OCIS codes: (250.5590) Quantum-well, -wire and -dot devices; (250.5980) Semiconductor optical amplifiers; (320.0320) Ultrafast optics; (320.2250) Femtosecond phenomena; (250.4390) Nonlinear optics, integrated optics.

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1. Introduction

The ultrafast dynamics of semiconductor nano structured (quantum dot (QD) and quantum dash (QDash)) optical gain media play crucial roles in determining their basic saturation and dephasing mechanisms. Nonlinear responses on time scales longer than 100 fs have been characterized often using single wavelength pump-probe techniques [1–3] and are reasonably well understood. The inhomogeneously broadened nature of these gain media requires that multi-wavelength pump-probe schemes be employed in order to obtain a detailed understanding of the cross saturation dynamics. Such experiments were reported recently [4] for the quasi-linear and highly saturated regimes where the phenomenon of a nearly instantaneous gain response [5] was identified. That unique response was found to be due to two-photon excitation by an intense stimulating pump pulse followed by fast carrier-carrier scattering relaxations to the ground states of all QDashes resulting in an immediate gain increase all across the inhomogeneously broadened gain spectrum.

However, some important nonlinear processes take place on time scales of only tens of fs. These imprint a nonlinear signature on the perturbing (pump) pulse itself and cannot be observed in a pump-probe experiment. Such ultrafast processes can be characterized using the techniques of frequency-resolved (or cross frequency-resolved) optical gating (FROG or X-FROG) [6,7] which measure amplitude and phase changes experienced by a pulse upon propagation in a nonlinear medium with a temporal resolution which can be a fraction of the pulse width.

Very few FROG and X-FROG measurements of an active semiconductor device were reported previously. FROG systems were used to characterize the output pulses of a QD mode locked laser [8] and for the investigation of 2 ps wide pulses after propagation through bulk semiconductor optical amplifiers [9]. The X-FROG technique was used to study short pulse propagation in passive GaAs V-grooved quantum wire waveguides [10] and in a bulk optical amplifier [11]. No FROG or X-FROG characterization of an inhomogeneously broadened nanostructured gain medium was reported previously. Short pulse propagation through a QD amplifier was measured [12] for the purpose of obtaining a controlled delay. However, that experiment used cross correlations between the amplified pulse and a replica of the original pulse yielding only information about the convoluted pulse shape distortion and the pulse arrival time but offered no knowledge about the phase. Moreover, the time resolution of such a cross correlation measurement is naturally limited by the width of the pulse.

A different technique for extracting the complex characteristics of an optical pulse, of a few picoseconds or longer durations, uses linear spectrograms [13] as demonstrated, for

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example in [14] where picosecond pulses propagating through a semiconductor optical amplifier were analysed.

In this paper, we report on measurements of the full time-resolved complex electromagnetic field (namely phase and amplitude) of 150 fs wide pulses propagating in an inhomogeneously broadened, 1550 nm InAs / InP QDash optical amplifier. The X-FROG technique which we employed reveals several unique characteristics of the quantum-wire-like [15] gain media, in particular when operating under high excitation levels. We quantified the dependences of pulse shape and phase changes on the amplifier bias level and on the input optical pulse energy. For pulse energies of up to ~300 pJ, the amplifier exhibits low to moderate saturation which causes relatively small distortions and chirp in both the gain and absorption regimes. For much larger input pulse energies and bias levels, the pulse shape is modified as a two-photon-induced instantaneous-gain response [5] initiates the buildup of a second peak.

2. Experimental results

The experimental setup is shown schematically in Fig. 1(a). A 1.5 mm long QDash amplifier whose structure is described in [4], is placed in one arm of a standard X-FROG system [7] which is fed from a tuneable source generating 150 fs pulses at 80 MHz with a maximum pulse energy of several nJ. The amplified spontaneous emission spectrum at a bias of 180 mA is shown in Fig. 1(b) while an exemplary X-FROG trace measured at a bias of 250 mA for a pulse energy of 1250 pJ is shown in Fig. 1(c). The time-frequency map obtained from the X-FROG system is analysed using a commercial software [16] yielding the time-dependent pulse electric field intensity and phase at the amplifier output. The measured X-FROG traces were down-sampled to 512 by 512 points and the retrieval algorithm yielded an error smaller than 0.003. Time-dependent intensity and instantaneous frequency-shift data extracted from X-FROG traces are shown in Fig. 2, and 4 below with their intensity peaks normalized and their corresponding timing placed at zero for clarity.

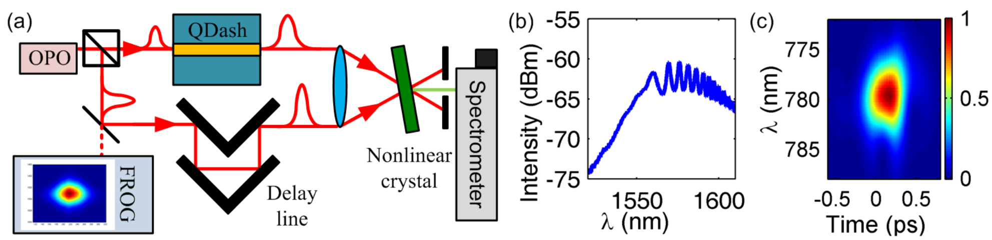

Fig. 1. (a) Principal experimental setup of the X-FROG system. (b) Amplified spontaneous emission spectra at a bias of 180 mA. (c) Exemplary X-FROG trace at a bias of 250 mA with a 1250 pJ pulse.

2.1 Quasi-linear and moderate saturation regime

Typical X-FROG results are shown in Fig. 2. The quasi-linear regime where the input pulse energy was 0.78 pJ, is described in Fig. 2(a) and 2(b) for three bias levels together with the reference input pulse. The corresponding small-signal chip gain values and the input saturation energies were 11 dB, 17 dB and 20 dB; 2 pJ, 1.5 pJ and 0.7 pJ, for bias levels of 100 mA, 150 mA and 200 mA, respectively. The envelope (Fig. 2(a)) exhibits minor distortions and barely varies with current changes. The instantaneous frequency-shift, $\Delta\nu(t)$, which is shown in Fig. 2(b) is derived from the measured time-dependent phase. As carriers are removed by stimulated emission, the group index increases and $\nu(t)$ is reduced. The frequency-shift increases with bias due to a combination of the moderate α parameter (stemming from the asymmetric carrier distribution in the wire-like QDash density of states function [15]) and the deeper saturation level under large drive currents. The maximum instantaneous frequency-shift at the peak of the pulse is ~4 THz. Previous chirp measurement in similar QDash amplifiers [17] with much wider, 800 ps, pulses yielded frequency shifts of

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~4 GHz. The increase by three orders of magnitude is consistent with the ratio of the rate of power change [18] (rise times) between the two vastly different pulses. All the above observations indicate that the saturation effects at these input energies are mainly due to intra-dash processes and that complex interactions with the wetting layer (discussed below) do not leave any signature on the response at these low pulse energies. An examination of the pulses arrival time on an absolute common time axis showed a bias dependant delay which is on the order of few tens of fs, consistent with the measurements shown in [12].

More intense pulses cause deeper saturation which depletes the wetting layer during the pulse resulting in a more significant pulse distortion. Figure 2(c) and 2(d) describe the characterization of pulses at 1550 nm having an input energy of 286 pJ. These were measured with a different reference pulse. The intensity traces (Fig. 2(c)) are very asymmetric due to gain saturation which occurs in the early part of the pulse and is sensed by its trailing edge. The time-resolved instantaneous-frequency shift traces (Fig. 2(d)) show a degree of non-monotonicity (mainly in the leading edge) due to a carrier exchange between the wetting layer and ground state during the interaction. The general predictable trend of larger frequency shift at increased bias is clearly maintained. Interestingly, the recovery rate of the frequency shift in Fig. 2(d) at large bias levels is faster than at lower currents and is due to the deeper carrier-depletion level, in contrast with the quasi-linear regime (Fig. 2(b)) where this rate is bias independent. The frequency shift is actually smaller than that in the quasi-linear regime because of a combination of several independent nonlinear mechanisms [19].

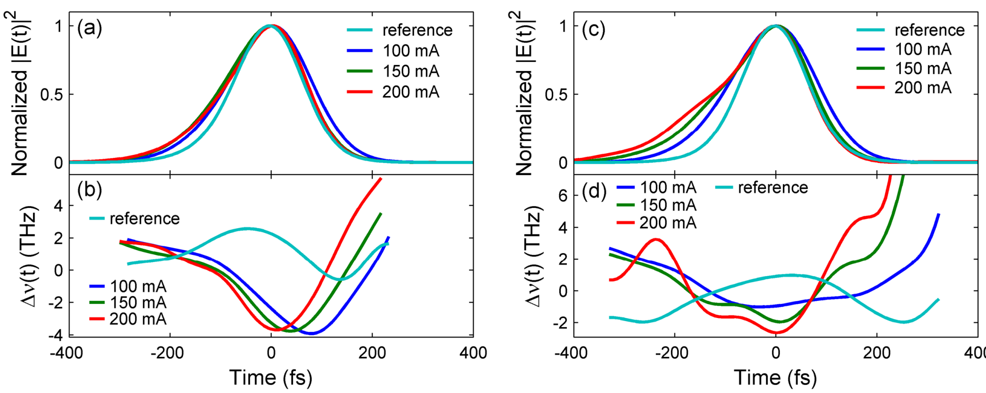

Fig. 2. Bias-dependent time-resolved intensity (a) and instantaneous frequency-shift (b) in the quasi-linear with an input pulse energy of 0.78 pJ and the saturated (c) and (d), for an input pulse having energy of 286 pJ, regimes. The input pulses are shown for reference and the peak intensities are normalized and placed at t = 0 for clarity.

The instantaneous frequency-shifts (Fig. 2 (b) and (d)) can be viewed as a spectral shift towards longer wavelengths. Figure 3(a) and Fig. 3(b) show bias dependent average pulse spectra for the 0.78 pJ and 286 pJ input pulses, respectively. A clear red shift is observed in both cases and the higher energy pulses also cause some asymmetry mainly for the largest bias. This frequency-shift has significant implications at larger input energies when the response is dominated by two-photon interactions as will be discussed later in this paper. The slight spectral distortion is related to the non-monotonic instantaneous frequency under high-bias conditions seen in Fig. 2(c) and (d).

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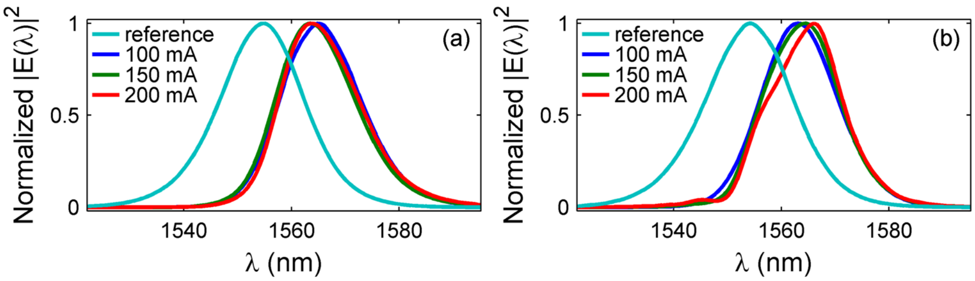

Fig. 3. Bias-dependent average output spectra of a pulse with an energy of (a) 0.78 pJ and (b) 286 pJ. The input pulse spectra are shown for reference. The peak intensities are normalized.

The QDash amplifier was also tested in the absorption regime for a pulse with an energy of 27 pJ and a bias level of 60 mA (Fig. 4). The pulse shape and the time-dependent instantaneous frequency remain symmetric with the pulses experiencing some broadening due to some modification of the absorption coefficient during the pulse, and the frequency-shift being smaller than in the quasi-linear amplification regime due to the weaker interaction with the active gain levels.

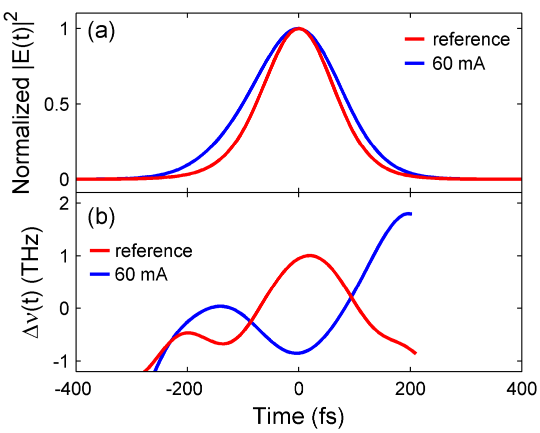

Fig. 4. Time-resolved intensity (a) and instantaneous frequency-shift (b) in the absorption regime at a bias of 60 mA with an input pulse having energy of 27 pJ. The peak intensities are normalized.

2.2 Deep saturation: two-photon dominated regime

The most interesting responses were observed for extremely large input energies. In a recent experiment [20], we have demonstrated that pulse with an energy of about 1000 pJ can cause laser oscillations in the same QDash amplifier reported here. These laser oscillations can be initiated by pulses whose wavelength is significantly longer than the resulting laser oscillation wavelength. This means that the required gain can only be induced indirectly by a nonlinear process; in this case two-photon absorption. Here we describe the effect of the nonlinear interaction on the pulse itself.

Intensity traces are shown in Fig. 5 for a 1250 pJ input pulse. The intensity peaks are not normalized in this case and the output arrival times are shown on an absolute common time axis. The figure compares responses in the absorption and gain regimes (measured at bias levels of 40, 150 and 250 mA). At 40 mA, the pulse peak is attenuated rapidly thereby experiencing virtually no nonlinear distortion. This measurement is used to determine the global pulse arrival time at the amplifier output (seen here at ~100 fs). At large bias levels, the output signal comprises two distinct peaks. The temporal position of the first peak coincides with the reference pulse (measured at 40 mA) while its intensity increases with bias and

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eventually saturates. The second peak emerges some 200 fs later as the bias is increased with its intensity growing monotonically.

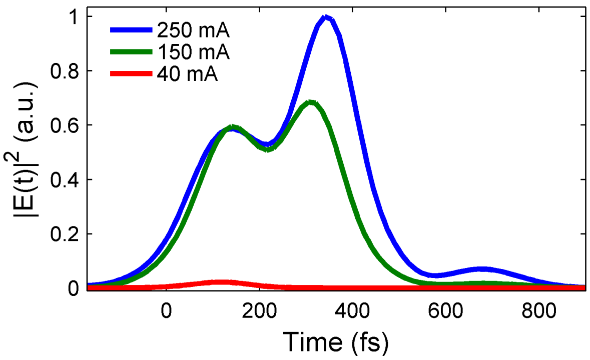

Fig. 5. Temporal intensity at bias levels of 40 mA, 150 mA and 250 mA with an input pulse energy of 1250 pJ.

We postulate that the trailing peak observed in Fig. 5 results from the two-photon-induced nearly instantaneous gain response [5, 20]. The leading edge and the peak of the pulse induce significant two-photon excitation which translates, following fast relaxation by carrier-carrier scattering, to an increase in the ground state population and hence the gain [5].

The fact that the trailing peak is due to two-photon-induced gain is supported by the more detailed presentation shown in Fig. 6. The figure shows normalized amplitudes (in solid lines) and the instantaneous frequency-shifts (in broken lines) for the reference pulse (Fig. 6 (a)) and for the three bias levels shown in Fig. 5 (Fig. 6 (b)-(d)). Concentrating on the instantaneous frequency-shift for the 150 mA and 250 mA cases where the double peaked pulse is observed, the leading pulse experiences a frequency-shift in the usual manner: The frequency reduces during the leading edge and recovers beyond the pulse peak. Figure 6 (c) and (d) reveal that the instantaneous frequency-shift associated with the second peak behaves in exactly the same manner: the frequency reduces first and recovers once the pulse reached its peak. These observations are a clear signature of two independent amplification processes; the first being conventional stimulated emission and the second being an instantaneous gain response induced by two-photon excitation.

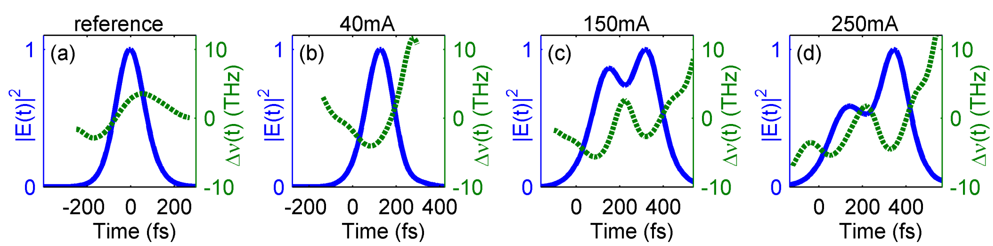

Fig. 6. Normalized intensity (solid lines) and instantaneous frequency-shift (broken lines) for the reference pulse (a), and a bias of 40 mA (b) 150 mA (c) 250 mA (d) with an input pulse energy of 1250 pJ. Traces (a)-(d) share a common absolute time axis.

Pulse break-ups were observed [11] and modelled [21] previously for bulk amplifiers but those differ from the observations we describe in Fig. 5 and 6. The previous observations [11] occurred for input energies of roughly 100 pJ (about one order of magnitude lower than for the present QDash amplifier) and were attributed to a combination of self-phase modulation, high-order nonlinearities and dispersion. However, the fact that the timing of the two observed peaks in Fig. 5 and 6, as well as their dependence on bias, are consistent with the instantaneous gain responses [5], and the fact that such pulses have been shown to induce laser oscillations [20], lead to the conclusion that the observed pulse break-ups in [11] differ from what is reported here.

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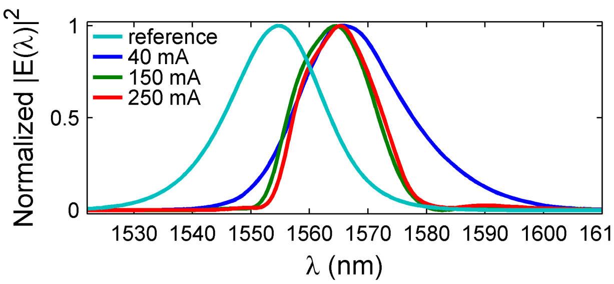

Fig. 7. Bias-dependent average output spectra of a pulse with energy of 1250 pJ. The input pulse spectrum is shown for reference. The peak intensities are normalized.

The various nonlinearities including two-photon absorption are distributed processes which mainly take place in the first part of the amplifier. The small confinement in nanostructured media enables these processes to accumulate over large parts of the amplifier length and therefore their efficiency increases. Furthermore, the spectral contents of the different pulses shown in Fig. 6 show that propagation causes the pulse to red-shift as seen in Fig. 7. Namely, its spectrum moves to a regime where saturation is smaller to begin with, thereby enhancing the gain sensed by the second peak. These effects enable the late part of the pulse to increase continuously upon propagation and to reach a higher output level than the leading part. The bias dependence of the second peak and its delay relative to the first pulse (200 fs, consistent with carrier-carrier relaxation [22]) support the fact that it results from the instantaneous gain response [5]. If the trailing edge is also distorted due to other nonlinear processes [11,21], that distortion is also amplified and further emphasized. Finally, we observe in Fig. 5 a third, very weak, pulse arriving at ~700 fs for the 250 mA bias. This could be the signature of pulse break up due to a combination of nonlinear processes [11] which is enhanced by the long lived gain component of the two-photon-induced gain [5].

Full characterization was also carried at wavelengths of up to 1590 nm showing basically the same behaviour thereby demonstrating the true inhomogeneity of the QDash gain media.

3. Summary

To conclude we have described high-resolution measurements of time-dependent amplitude and phase responses of short pulses propagating in an inhomogeneously broadened InAs/InP QDash amplifier using the X-FROG technique. We showed that in the quasi-linear and absorption regimes the pulse propagation is governed mainly by the intra-dash dynamics. In the saturation regime, additional processes which involve deep depletion of the wetting layer take place. For high input energies and large bias levels, a second peak emerges which stems from amplification, due to a two-photon-induced instantaneous gain response, of the late portions of the pulse. This constitutes a direct time-domain observation of the instantaneous gain response which was previously observed by pump-probe measurements [5].

Acknowledgments

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