Technical University of Denmark

DTU

Tunable propagation delay of femtosecond pulses in a quantum-dot optical amplifier at room temperature

Poel, Mike van der; Mørk, Jesper; Hvam, Jørn Marcher

DTU Library
Technical Information Center of Denmark

Tunable propagation delay of femtosecond pulses in a quantum-dot optical amplifier at room temperature

M. van der Poel, J. Mørk, and J.M. Hvam

Research Center COM, Technical University of Demnark, DK-2800 Kgs. Lyngby

E-mail: mvp@com.dtu.dk, fax: +45 4593 6581

Abstract: Optically induced dispersion over a large bandwidth of 2.6 THz is used to slow or speed up a 150 fs pulse in a quantum-dot optical amplifier. A group refractive index change of $4*10^{-3}$ is observed.

©2000 Optical Society of America

OCIS codes: (250.5980) Semiconductor optical amplifiers; (190.5530) Pulse propagation and solitons

1. Introduction

The potential of realizing tunable propagation delay of optical pulses using strong, optically induced dispersion in an optical medium has attracted great attention since the pioneering experiments by Hau et al. [1]. Such a tunable propagation delay opens up for optical memory capacity which in turn allows a whole new class of optical components in optical communications systems and signal processing [2]. Recent demonstrations of tunable propagation delay of optical pulses in solid-state optical media [3] at room temperature and in semiconductor quantum wells [4] at cryogenic temperatures suggest that it might be possible to achieve this kind of functionality in practical components.

The above mentioned results showed a large change in group velocity but this was achieved at the cost of a small bandwidth (e.g. 37 Hz in the case of Bigelow *et al.* [3] or 2 GHz in the case of Ku *et al.* [4]) of the probe signal. In this paper we report measurements of slowing down and speeding up of the propagation of a 150 fs pulse, having a very large bandwidth of 2.6 THz, through a quantum-dot (QD) semiconductor amplifier (SOA) at room temperature. This extremely large bandwidth, on the other hand, is at the cost of a rather small group index change of $\Delta n_g = 4*10^{-3}$.
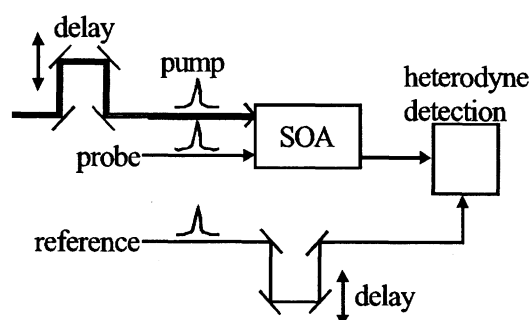
2. Experiment and sample details

a)
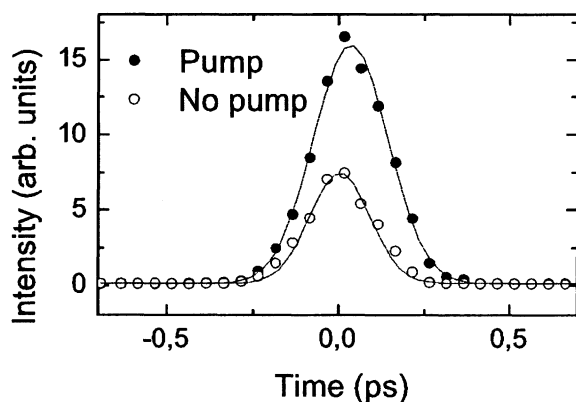
b)

Fig. 1. a) Measurement of pulse delay through cross correlation traces of probe pulse with reference pulse at zero bias current. A 20 fs slow down of the probe pulse is caused by the presence of a pump pulse. Pump bleaching of the absorption also increases the probe transmission. b) Schematic overview of experimental setup.

Cross-correlation traces of a weak probe pulse propagated through a ridge-waveguide QD SOA and a reference pulse were recorded in a heterodyne detection setup described in [5] shown shown schematically in Fig. 1b. Comparison of cross-correlation traces recorded with and without the presence of a strong pump pulse showed changes of probe propagation time, intensity and pulsewidth caused by the pump. An example of this is shown in Fig. 1a. The time shift Δt, for instance, between arrival time of the probe pulse with and without the presence of the

pump pulse is related to the pump-induced change in group index Δn_g by $\Delta n_g = c\Delta t/L$, where c is the speed of light and L is the length of the component. These pump-induced changes were recorded as function of injected current and pump-probe delay time.

The 2 mm long and 7 μm wide ridge-waveguide SOA had an active layer of 5 sheets of self-organized InAs/InGaAs/GaAs QDs [6] showing a central ground state emission at 1260 nm. The pump, probe and reference pulses were derived from a Ti:Sapphire + regenerative amplifier + optical parametrical amplifier cascade (Coherent Inc.) delivering near-transform limited pulses with 150 fs duration and wavelength tunable in the 950 – 2000 nm range. In the experiments reported here, the wavelength was tuned to 1273 nm – slightly above the GS emission wavelength. The pump intensity is close to the saturation intensity of the amplifier, while the probe intensity, being about two orders of magnitude smaller, is in the small-signal regime.

3. Results and discussion

The pump-induced change in probe travel time for different bias currents at zero pump-probe delay is shown in Fig. 2. For the zero injected current, a pump-induced delay of the probe of 17 fs is seen. As bias current is increased the slowdown diminishes, changes sign, and becomes a speeding up of 10 fs at high injected current. We qualitatively interpret this behavior in the following way: At zero bias the pump pulse injects a population of carriers into the QD ground state. These carriers result in a spectral gain and index feature centered on the pump wavelength resulting in a decreased probe group velocity. At high injection current the pump pulse burns a spectral hole creating a spectral feature of similar nature as for zero bias current, but of opposite sign resulting in an increased probe group velocity. In order to understand this quantitatively we write the optical susceptibility seen by the probe, χ, as

$$\chi(\omega) = \int_0^\infty d\omega' \frac{Ne^2|D|^2}{3\varepsilon_0 \Box} \frac{\omega' - \omega + i\gamma'}{(\omega' - \omega)^2 + \gamma'^2(1 + s_0)} + \chi_{bg} \tag{1}$$

where $N = (N_{gr} - N_{ex})$ is the difference in density of ground and excited state dots, e is the fundamental charge, D is the QD dipole moment, ε_0 is the vacuum permittivity, $\Box$ is Planck's constant, $\Box\gamma'$ is the homogeneous QD linewidth, s_0 is an intensity saturation parameter, and χ_{bg} is the background susceptibility. Note that the inhomogeneous QD broadening and the laser linewidth are included in Eq. 1 through the frequency dependence of N and s_0. Given the susceptibility, the group index n_g can be calculated as

$$n_g = \sqrt{1 + \chi} + \omega \frac{d}{d\omega} \sqrt{1 + \chi} \tag{2}$$

For the case of zero injection current, and using realistic parameters for our SOA, Eq. 1 gives a maximum slowdown of 31 fs, in reasonably good agreement with experiment. Furthermore, Eq. 1 predicts that the pump-induced change of the probe travel time through the amplifier is proportional to the dot inversion. The dot inversion itself is proportional to the logarithm of the on-chip gain. In Fig. 2 this proportionality of delay time and logarithm of on-chip gain is clearly demonstrated.
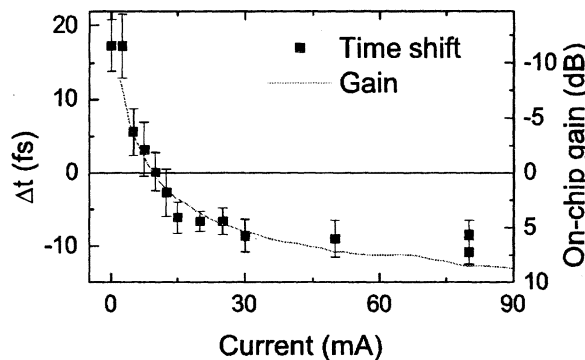

Fig. 2. Left axis: pump-induced change in probe travel time as function of injection current. Right axis: Independently measured small signal gain of the amplifier.

The pump injected carriers at zero bias current have a lifetime of the order of 100 ps. At the same time, the amplified spontaneous emission from the amplifier shows a separation of 60 meV between the ground-state and the excited-state, several times larger than the room temperature thermal energy. Together, the long lifetime and large dot level separation imply the persistence of the pump-induced susceptibility long after passage of the probe pulse. Fig. 3 shows the pump-induced change in probe travel time at zero bias current as function of pump-probe delay time. The decay in probe delay time matches well the decay in the pump-induced difference in probe transmission also shown in Fig. 3. Again, the differential transmission reflects the change in pump-induced dot inversion. This behavior is therefore in agreement with the expectations from Eq. 1. The slightly faster decay of the probe slowdown compared to the differential probe transmission seen in Fig. 3 suggests some degree of spreading of the pump-injected carriers. In the gain region of the SOA, the probe speed up does not persist to long pump-probe delays. This is due to the fast, picosecond recovery of the pump-induced spectral feature which is possible through intra-dot relaxation.
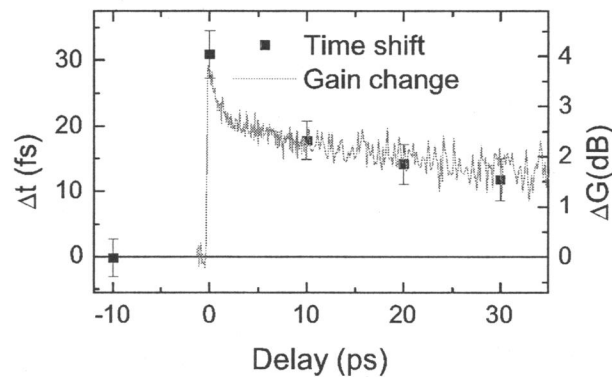

Fig. 3. Left scale: pump-induced change in probe travel time as function of pump-probe delay. Right scale: pump-induced change in probe transmission.

4. Conclusion

We have demonstrated optical tuneability of the travel time of a probe pulse propagating trough a QD SOA. The overall change in travel time was 30 fs corresponding to a group velocity index change of $\Delta n_g = 4*10^{-3}$. The bandwidth over which this delay occurs is 2.6 THz.

The results are interpreted in a simple model of the pump-induced changes in optical susceptibility, which explains well the observations. The mechanism behind the slowing down and speeding up of the pulse is related to, but no similar to the effect of coherent population oscillations described in litterature [3] in the sense that it relies on the carrier lifetime in the excited state but is relatively insensitive to quantum decoherence of those carriers.

4. Acknowledgements

5. References

[1] L.V. Hau, S.E. Harris, Z. Dutton, and C.H. Behroozi, "Light speed reduction to 17 meters per second un an ultracold atomic gas", Nature **397**, 594—598 (1999)

[2] C.J. Chang-Hasnain, P.-C. Ku, J. Kim, S.-L. Chuang, "Variable optical buffer using slow light in semiconductor nanostructures", Proc. IEEE **91**, 1884—1897 (2003)

[3] M.S. Bigelow, N.N. Lepeshkin, and R. Boyd, "Observation of ultraslow light propagation in a ruby crystal at room temperature", Phys. Rev. Lett. **90**, 113903-1—4 (2003)

[4] P.-C. Ku, F. Sedgwick, C.J. Chang-Hasnain, P. Palinginis, T. Li, H. Wang, S.-W. Chang, and S.-L. Chuang, "Slow light in semiconductor quantum wells", Opt. Lett. **19**, 2291—2293 (2004)

[5] P. Borri, W. Langbein, J. Mørk, and J.M. Hvam, "Heterodyne pump-probe and four-wave mixing in semiconductor optical amplifiers using balanced lock-in detection", Opt. Comm. **169**, 317—324 (1999)

[6] A.R. Kovsh et al., "InAs/InGaAs/GaAs quantum dot lasers of 1.3 mm range with enhanced optical gain", J. Crystal Growth **250**, 729 (2003)