# Phase-shift stabilization of 500 Gbit/s ultra-short optical pulses in a semiconductor optical amplifier by Manchester encoding

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*We present simulation results of the time-evolution of a pulse-train consisting of 200 fs optical pulses at an effective bit-rate of 500 Gbit/s in a semiconductor optical amplifier (SOA). The SOA slow recovery could lead to pattern effects in the output pulses. We show that the output power of the amplified data pulses can be stabilized when Manchester encoding is used. The simulation results show that this technique is suitable for applications in practical ultra-fast switching device operation.*

## 1. Introduction

Semiconductor optical amplifiers (SOAs) have great potential as nonlinear elements for all-optical signal processing in high-speed telecommunication systems [1-3]. The response of SOAs to ultrashort optical pulses has been becoming a subject of extensive experimental and theoretical studies [4-7]. Recently, the optical time division multiplexing technique was used to obtain single-channel data transmission at 1.28 Tbit/s [8]. The study of sub-picosecond pulses in SOAs is of practical importance for a single-channel transmission at 1 Tbit/s. Traditionally, the data rates of SOAs are limited by the pattern effects induced by gain recovery, which are typically about several hundred picoseconds. However, on the sub-picosecond timescale, the most important relaxation processes in SOAs are due to intra-band dynamics that occur after two-photon absorption (TPA) and free-carrier absorption (FCA)[5].

In an earlier study we have used a numerical model to simulate the dynamics associated with a train of optical pulses at 1 Tbit/s repetition rate [5]. The pulse train had a duration that was sufficient to bring the SOA well into saturation. The simulations in Ref. [5] were carried out to numerically investigate practical switching conditions using a SOA and high bit rate data streams. We have shown that even at such a high repetition rate phase changes were introduced that were sufficient for all-optical Terahertz switching and logics [9]. However, when a high bit rate control signal inputs the SOA, the output data pulses will suffer from strong pattern effects due to the gain recovery. For instance, when two control “0”s appear consecutively at the SOA input, the second data pulse will experience a larger gain. Hence, the second data pulse experiences a larger amplitude and phase shift compared to the first data pulse. It is important that such deleterious effects should be overcome in practical switching device applications. In this paper we will show on the basis of simulations that in case of Manchester encoded control pulses this problem does not take place.

## 2. Model

The model and details are described in Ref. [5], which is an extension of results presented in Ref. [4]. The model accounts for Two Photon Absorption (TPA) and Free Carrier Absorption (FCA) as well as self and cross Phase Modulation (PM). The SOA parameters used in our simulations are collected in Table 1.

**Table 1**: SOA parameter definitions and their values.

| Parameter | Symbol | Value | Unit |
|---|---|---|---|
| Active volume | $V = L \times W \times D$ | 150×1×0.1 | $\mu m^3$ |
| Confinement factors | $\Gamma, \Gamma_2$ | 0.2, 0.5 | |
| Phase modulation coefficients | $\alpha, \alpha_2$ | 7, 2 | |
| Electron-hole pair lifetime | $\tau_s$ | 250 | $ps$ |
| Gain coefficient | $a(\omega_0)$ | $5.3\times10^{-5}$ | $\mu m^3 / ps$ |
| Group velocity | $v_g$ | 100 | $\mu m / ps$ |
| Internal loss | $\alpha_{\text{int}}$ | 0.00175 | $\mu m^{-1}$ |
| Optical transition energies | $E_c, E_{2c,}$ | 0.03, 0.7 | $eV$ |
| Optical transition energies | $E_v, E_{2v}$ | 0.003, 0.07 | $eV$ |
| Carrier-carrier scattering times | $\tau_{1,c}, \tau_{1,v}$ | 0.1, 0.05 | $ps$ |
| Carrier-phonon relaxation times | $\tau_{h,c}, \tau_{h,v}$ | 0.7, 0.25 | $ps$ |
| FCA coefficients | $\beta_v, \beta_c$ | $0, 1\times10^{-9}$ | $\mu m^2$ |
| TPA coefficient | $\beta_2$ | $7.5\times10^{-7}$ | $\mu m^2$ |
| Optical transition state density | $N_0$ | $9.3\times10^{5}$ | $\mu m^{-3}$ |

## 3. Results and discussion

We consider the case when two parallel trains of several hundreds equidistant pulses at equal repetition rates are injected into the SOA. One pulse train consists of saturating (control) pulses with 0.5 pJ (per pulse). The other pulse train consists of low-energy data pulses with 0.2 fJ (per pulse). The number of control pulses has to be so large that the SOA becomes strongly saturated. The delay between the pump and probe pulses is optimised to ensure that the probe pulse propagates through the gain minimum introduced by the pump pulse. The schematic configuration used in our simulation is shown in Figure 1. We consider a control pulse train has the following sequence: l010011011. This control pulse train enters the SOA after it is saturated with 200 control pulses.

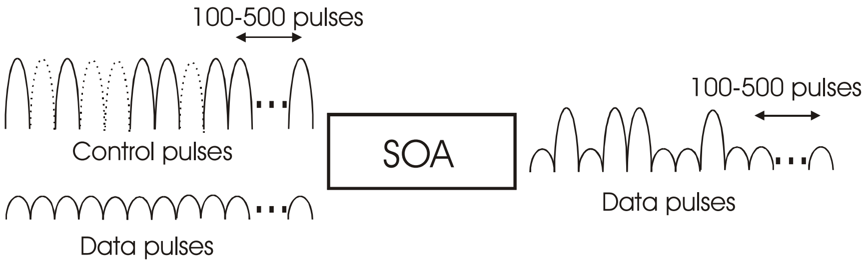
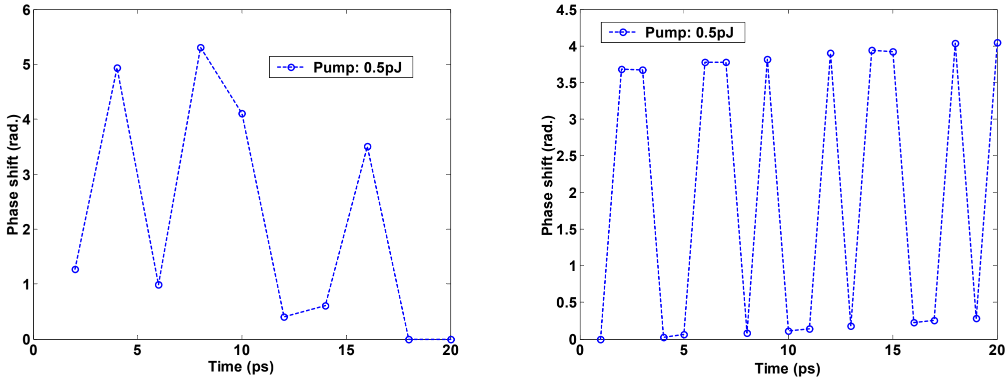



**Figure 1**: Control and data pulses configuration for simulation of data pulse evolution, where a serial of the control pulses train: l010011011 is introduced after repetitive 100-500 pulses.




(a) (b)

**Figure 2**: Nonlinear phase-shift variation of the data pulse train when a serial of random control pulse train is introduced after repetitive 200 pulses in SOA, where data and control pulse widths are 200 fs, data and control pulse energy are 0.2 fJ and 0.5 pJ respectively, I=400mA, the values are taken at the peak of each pulse. (a). The control pulse train is l010011011 at 500 Gbit/s;(b). Manchester-coded control pulse train: l0011001011010011010, with the same data as (a) for control pulse train, at effective data-rate 500 Gbit/s. (Note that the data pulses are inversed in the output pulse sequence)

At high bit-rate applications, the SOA works in a strongly saturated equilibrium state that is induced by repetitive strong saturating optical control pulses. The nonlinear phase-shifts of a series of data pulses are plotted in Figure 2. This result presented in Figure 2 is obtained for a random control pulse train at 500 Gbit/s. In Figure 2(a), we have used Return to Zero data and control pulse trains at 500 Gbit/s, where each bit of "0" and "1" stands for one bit of signal. In contrast to this, we have used data and control pulse trains that are Manchester encoded in Figure 2(b) at a bit rate of 1 Tbit/s (the effective data rate is 500 Gbit/s).

In both cases of Figure 2(a) and 2(b), we can clearly see that the nonlinear phase-shift of data pulses changes significantly whenever the control pulse is absent. A phase-shift larger than π radians can be observed when the pump pulse energy is 0.5 pJ. The phase-shift instability in Figure 2(a) is about 1.2 radians in the peak when two "0" appears in control pulse train. However it follows from Figure 2(b) that the phase instability has been reduces to 0.2 radians when two Manchester encoded control "0" arrive at the SOA. This is due to the constant average optical power inside SOA for the later case, which results in a stable amplification of the data pulses, especially in the case that "0" or "1" appear in a random control pulse train. It should be mentioned that, the Manchester encoding reduces the effective data-rate to be one-half of the real pulse bit-rate. In addition, a pump pulse energy 0.5 pJ at 500 Gbit/s equals to 250 mW in average optical power, which is too much to be handled by a general SOA, however the average optical power could be reduced by employing control pulses shorter than 200 fs (FWHM).

## 4. Conclusions

For the needs of practical device operation, numerical results have been presented to investigate the evolution of 200 fs (FWHM) optical pulses and a long bit pulse train in a saturated SOA at 500 Gbit/s repetition rate. The SOA model accounts for the ultrafast intraband nonlinear processes such as TPA, FCA and PM. We have introduced a technique to stabilize the average optical power inside the SOA by using Manchester encoding of the control signal. The simulation results show this technique is helpful to stabilize the nonlinear phase-shift of the data pulses after the SOA. A significant ($>\pi$) phase difference of the data pulse can still be obtained with strong injected current density at 500 Gbit/s repetition rate. These results suggest that the SOA could be a good candidate for applications as ultrahigh speed all-optical logics with sub-picosecond optical pulses.

## Acknowledgement

This work was supported by the Netherlands Organization for Scientific Research (NWO) through the "NRC Photonics" grant.

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