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Temporally flat top pulse generation from gain switched semiconductor lasers based on a polarization interferometer with variable transfer function

Antonio Consoli *, Ignacio Esquivias

Departamento de Tecnología Fotónica y Bioingeniería—CEMDATIC, Universidad Politécnica de Madrid, Ciudad Universitaria, 28040 Madrid, Spain

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ABSTRACT

We propose the use of a polarization based interferometer with variable transfer function for the generation of temporally flat top pulses from gain switched single mode semiconductor lasers. The main advantage of the presented technique is its flexibility in terms of input pulse characteristics, as pulse duration, spectral bandwidth and operating wavelength. Theoretical predictions and experimental demonstrations are presented and the proposed technique is applied to two different semiconductor laser sources emitting in the 1550 nm region. Flat top pulses are successfully obtained with input seed pulses with duration ranging from 40 ps to 100 ps.

1. Introduction

Optical pulses with duration of tens of picoseconds find application in a wide variety of fields: optical communication channels, imaging, material processing, sensing, optical scanning and ranging [1]. Pulse temporal profile is often relevant, as specific applications require the use of particular pulse shapes. This is the case of flat top pulses which are employed in a large variety of applications, e.g. retiming of high data bit rate optical communication channels in C band [2], efficient pumping of free electron lasers in the deep Ultra Violet wavelength region [3] and amplitude and phase characterization of ultra-short pulses [4].

Common methods for flat top pulse generation are based on spectral filtering of Gaussian, transform limited, ultra-short pulses obtained from mode locked lasers [5]. The general approach is based on pulse spectral filtering by means of a specifically designed photonic device, adapted to the intensity and phase profiles of the seed pulse. The required photonic filter can be implemented with interferometers [6–8], Fiber Bragg Gratings (FBGs) [9–11] or optical differentiators [12,13].

Usually there is a compromise between device design, implementation and tunability. All fiber implementation is usually designed only for a specific input pulse, which has been previously carefully characterized. Free optics elements and movable parts allows the modification of the photonic filter Transfer Function (TF) and tunability of the device in terms e.g. of obtainable output pulse profiles, operating wavelength and input pulses. The most general case of arbitrary pulse shaping uses a pair of diffraction gratings and a programmable spatial mask: the spectral content is dispersed, properly filtered and then recombined [14]. This solution is widely flexible, but bulky. More recent works have reported fiber implementation and some degree of freedom on its TF given by mechanical action on the fiber. For example, in [7] the Extinction Ratio (ER) of a dual mode fiber interferometer is tuned by twisting the dual mode fiber. In a similar way, in [12] the spectral transmission dip of the proposed differentiator is varied by applying axial straining to the Long Period Fiber Grating (LPFG). However, apart from the ER tuning, the spectral characteristics of the filter, e.g. the Free Spectral Range (FSR) of the interferometer or the central frequency of the differentiator, cannot be varied, thus fixing the operating wavelength and limiting the spectral characteristics of the allowed input pulses.

We have previously proposed a hybrid fiber and free space optics implementation of a polarization based 50:50 Mach–Zehnder (MZ) interferometer with variable delay, for pulse shortening of gain-switched (GS) single mode semiconductor lasers [15]. The spectral TF of the proposed device was properly tuned for suppressing the red frequencies side of the pulse spectrum, thus reducing the falling edge of the pulse temporal profile and its total duration. In [15] pulse shortening has been demonstrated with a Distribute Feedback (DFB) laser and a Vertical Cavity Surface

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* Corresponding author. Present address: Instituto de Ciencia de Materiales de Madrid (CSIC), c/Sor Juana Inés de la Cruz 3, 28049 Madrid, Spain. Tel.: +34913367366; fax: +34913367319.

E-mail addresses: antonio.consoli@upm.es, antonio.consoli@icmm.csic.es (A. Consoli).

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Emitting Laser (VCSEL), both emitting in the 1550 nm region. The pulse at the interferometer input had durations in the range of tens of picoseconds, typical of GS lasers, similar to the pulses presented in this work.

In this manuscript, we extend our previous work with the implementation of a polarization based interferometer, similar to the one presented in [15], in which the input coupling, output coupling and temporal delay between the two arms can be easily tuned. We demonstrate flat top pulse generation from a DFB laser and a VCSEL operating at different wavelengths in the 1550 nm region. Different pulses were generated from the GS devices by varying the gain switching parameters and flat top pulses are obtained in all cases by properly tuning the interferometer parameters.

This work is organized as follows: the principle of operation of the proposed technique and the performed numerical simulations are presented in Section 2; Section 3 describes the experimental results and in Section 4, the main conclusions are presented.

2. Principle of operation and numerical simulations

The principle of operation of the proposed technique is based on the use of a chirped pulse at the interferometer input. Pulse shaping is obtained with spectral amplitude filtering, based on the time-frequency correspondence of the input chirped pulse. The central part of the pulse spectrum, which corresponds to the pulse peak in time, is properly attenuated in order to flattens the pulse peak in time and obtain a flat top temporal profile at the interferometer output. This corresponds to use a notch-like filter, with minimum of transmission placed at the pulse spectrum central frequency and with suitable notch depth.

The proposed notch filter is an interferometer with variable TF, in which the ER can be changed by varying the coupling ratios between the two interferometer arms (k_1 and k_2) and its FSR can be tuned by varying the temporal delay τ between the interferometer arms. Experimentally, this solution is implemented with a polarization based interferometer, described in detail in Section 3.

Pulses at the interferometer input are generated by gain switching a semiconductor laser, which gives almost linearly chirped pulses. The entire system has been numerically simulated. Pulses at the interferometer input have been obtained in simulations using the density rate equations for photons, carriers and phase [15] with typical parameters for a 1550 nm DFB laser [16]. Pulses are generated by gain switching the laser with the current $I(t)$, given by the sum of a Direct Current (DC) term, I_{BIAS}, and a sinusoidal current with amplitude I_{AMP} and frequency f_{GS}, i.e. $I(t)=I_{BIAS}+I_{AMP}\cdot\sin(2\pi f_{GS}t)$.

The output pulse power, $P(t)$, and phase, $\phi(t)$, are obtained from the density rate equations and the pulse complex envelope is calculated as $E(t)=\sqrt{P(t)}\exp[j\phi(t)]$, where t is the time variable and j is the imaginary unit. The instantaneous frequency $\nu(t)$ is calculated from the time derivative of the phase, i.e. $\nu(t)=(2\pi)^{-1}d(\phi(t))/dt$.

The complex pulse spectrum is then obtained as $\tilde{E}(f)=FT[E(t)]$, where FT is the Fourier Transform operator and f the frequency domain variable.

Fig. 1 show the simulation results for $I_{BIAS}=I_{TH}$, $I_{AMP}=4I_{TH}$ and $f_{GS}=1$ GHz, where I_{TH} is the threshold current of the simulated laser. The gain switching parameters (I_{BIAS}, I_{AMP} and f_{GS}) have been chosen in order to have similar results in comparison with experiments. The simulated pulses have Full Width Half Maximum (FWHM) duration of about 65 ps and a spectral bandwidth at $1/e^2$ of 33.5 GHz.

Typical features of pulses from GS semiconductor lasers can be observed in Fig. 1(a): asymmetric temporal intensity profile and carrier induced negative variation of instantaneous frequency. In Fig. 1(b), the expected broadened spectrum, with intensity modulation due to the relaxation oscillations at this bias point, and the corresponding group delay are shown.

The interferometer TF, $H(f)$, of a MZ interferometer has been numerically implemented as $H(f)=j\sqrt{k_1(1-k_2)}+j\sqrt{k_2(1-k_1)}\exp(j2\pi f\tau)$ [17] where τ is the temporal delay between the two interferometer arms and k_1 and k_2 are the coupling ratios at the input and output coupler, respectively. For each optical coupler, the coupling ratio k is defined as the fraction of output power of the output port in direct pass to the total output power. The pulse spectrum at the interferometer output is calculated as $\tilde{E}_{OUT}(f)=\tilde{E}(f)H(f)$ and its temporal complex envelope, $E_{OUT}(t)$, is obtained after Inverse Fourier Transforming (IFT), as $E_{OUT}(t)=\mathrm{IFT}[\tilde{E}_{OUT}(f)]$.

In order to compare the simulated pulses at the interferometer output with an ideal rectangular pulse, we introduce a simple Flat Top Form Factor (FTFF), defined as:

$$\mathrm{FTFF}=\frac{\int_{t1}^{t2}\left[y(t)-y_{TH}\right]dt}{\int_{t1}^{t2}\left[rect(t)-y_{TH}\right]dt} \tag{1}$$

where $y(t)$ is the pulse under study, $rect(t)$ is an ideal rectangular pulse, with constant width given by $W=t_2-t_1$, and t_1 and t_2 are the time instants in which $y(t)$ crosses the threshold value y_{TH}. The FTFF definition is schematically depicted in Fig. 2.

The FTFF gives an estimation of how much the waveform under study resembles an ideal rectangular pulse with a given width, set by the threshold value y_{TH}. If $y(t)$ is an ideal rectangular pulse, FTFF=1, in any other case, FTFF<1 and its value depends on the shape of $y(t)$ and y_{TH}. We set y_{TH} equal to $1/e^2$ of the pulse maximum, which gives FTFF=0.48, for the simulated pulse with asymmetric intensity profile shown in Fig. 1.

We performed simulations with the aim of maximizing the FTFF of the output pulse, using at the interferometer input the

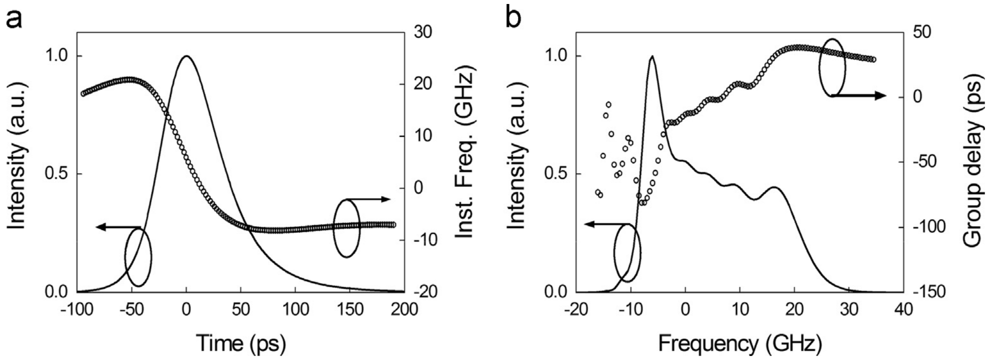

Fig. 1. Simulation results for the simulated GS DFB laser with $I_{BIAS}=I_{TH}$, $I_{AMP}=4I_{TH}$ and $f_{GS}=1$ GHz: (a) Temporal intensity (solid line, left axis) and instantaneous frequency (open circles, right axis) and (b) spectral intensity (solid line, left axis) and group delay (open circles, right axis).