Time resolved chirp measurements of gain switched semiconductor laser using a polarization based optical differentiator

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Abstract: We present a novel implementation of the "phase reconstruction using optical ultra fast differentiation" (PROUD) technique and apply it to characterize the time resolved chirp of a gain switched semiconductor laser. The optical temporal differentiator is a fiber based polarization interferometer. The method provides a fast and simple recovery of the instantaneous frequency from two temporal intensity measurements, obtained by changing the spectral response of the interferometer. Pulses with different shapes and durations of hundreds of picoseconds are fully characterized in amplitude and phase. The technique is validated by comparing the measured pulse spectra with the reconstructed spectra obtained from the intensity and the recovered phase.

OCIS codes: (060.0060) Fiber optics and optical communication; (120.5050) Phase measurement; (140.5960) Semiconductor lasers; (140.3538) Lasers, pulsed.

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1. Introduction

Short optical pulses, with durations ranging between hundreds of femtoseconds and hundreds of picoseconds, are commonly employed in different fields, including telecommunication, spectrometry, telemetry, material processing and others [1]. The complete characterization of such pulses, in amplitude and phase, continues to be an important scientific and technological challenge. In the case of pulses used in optical fiber communications, obtained by direct or external modulation of semiconductor lasers, the frequency chirp strongly affects the pulse propagation and therefore a complete characterization of the optical signal is often required. Furthermore, the new modulation formats used in high data rates systems, such as quadrature phase-shift keying, demand direct, simple and fast techniques able to provide the instantaneous frequency even for relatively low power levels.

Different methods have been developed for the complete characterization of short optical pulses [2]. Spectrographic techniques, e.g. frequency resolved optical gating (FROG) [3] and inteferometric techniques, e.g. spectral shearing interferometry for direct electrical field reconstruction (SPIDER) [4] are commonly employed in ultra short pulse experiments. Both types of techniques are based on a non-linear interaction of the pulse under test, having an intrinsic limitation on the sensitivity of the measurement, and hence are better suited for high power, low repetition rate femtoseconds pulse trains. Although linear versions of both

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SPIDER and FROG have been proposed and applied to telecommunication signals, they require the use of amplitude and phase modulators [5] and an iterative numerical algorithm [6]. The phase of an optical pulse can be also reconstructed from the measured temporal and spectral intensities by using iterative algorithms [7], as for instance the well known Gerchberg-Saxton algorithm [8], provided sufficient temporal and spectral resolutions are experimentally available.

In the context of communication signals, several techniques have been developed to characterize the instantaneous frequency, the so-called time-resolved chirp (TRC). They are based on frequency discriminators [9–12], Brillouin scattering interaction [13] and spectral phase measurements [14]. Recently, Li et al. [15,16] have proposed a different approach named "phase reconstruction by optical ultrafast differentiation" (PROUD). PROUD is based on the direct detection of the pulse intensity before and after filtering the signal with an optical differentiator and the application of a simple, non-iterative formula for recovering the instantaneous frequency. Unlike the frequency discriminator technique, the PROUD method takes into account the phase of the optical filter, i.e. the differentiator [15], resulting in a more accurate phase measurement.

In this work, we present a new implementation of PROUD based on the use as optical differentiator of a fiber based polarization interferometer and examine its potential for an accurate, simple and fast characterization of the TRC in optical signals used in communication systems. As a proof of concept, we analyze the chirp of the pulses generated by a gain-switched (GS) semiconductor laser. This type of pulses are employed in a rich variety of fields, such as high speed optical communication channels [17], pulse compression [18], pulse shaping [19], master oscillator power amplifiers [20,21], super continuum generation [22], and terahertz amplification [23]. Therefore, the accurate measurement of the instantaneous frequency of GS laser pulses is relevant for all these applications.

The paper is organized as follows: in section 2, PROUD is briefly sketched and our implementation of the technique is described in detail. In section 3, the TRC measurements of pulses obtained in different GS conditions are presented and discussed, and the potential and prospects of the technique for the characterization of signals in communications are analyzed. Finally in section 4, the main conclusions of the work are summarized.

2. Measurement technique and experimental set-up

The fundamentals of PROUD have been described and analyzed in detail in [15,16] and therefore we only sketch here the basic concepts required for the understanding of our implementation. Let $u(t) = \sqrt{I(t)}\exp(j\phi(t))$ be the temporal complex envelope of an optical pulse, with $I(t)$ being the pulse intensity, $\varphi(t)$ the pulse phase and $\omega_i(t) = d\varphi(t)/dt$ the pulse instantaneous frequency. Optical differentiation can be achieved by employing a filter with spectral transfer function $H(\omega) = jA(\omega - \Delta\omega)$, where A is the differentiator amplitude coefficient, ω is the base-band frequency, and $\Delta\omega = \omega_0 - \omega_R$ is the difference between the signal carrier frequency ω_0 and the differentiator resonance frequency ω_R [24]. Under the condition $|\Delta\omega| > |\omega_i(t)|$, the instantaneous frequency of the pulse can be recovered from the pulse intensity $|u(t)|^2$ and the intensity at the differentiator output $|v(t)|^2$, with the following direct expression [15]:

$$\omega_i(t) = \sqrt{\left[\left(\frac{|v(t)|}{A}\right)^2 - \left(\frac{d|u(t)|}{dt}\right)^2\right] \Big/ |u(t)|^2} - \Delta\omega. \tag{1}$$

It's worth noting that the condition $|\Delta\omega| > |\omega_i(t)|$ simply implies that the spectral bandwidth of the input signal is entirely positioned at either side of the differentiator resonance frequency. Then, the pulse phase can be obtained by numerically integrating the instantaneous frequency: $\varphi(t) = \int\omega_i(t)dt + \varphi_0$, where φ_0 is a non relevant constant.

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A key point of the technique is the requirement of synchronization between the measured intensities $|u(t)|^2$ and $|v(t)|^2$ for the validity of Eq. (1). Thus, in previous implementations of PROUD, the temporal delay between the input and output of the differentiator was measured and compensated. Our implementation avoids the need for time delay compensation, resulting in a significant simplification of the experimental apparatus and procedure. This is achieved by switching the spectral transfer function of the filter in such a way that the differentiator transfer function is used to measure $|v(t)|^2$ and a plain transfer function is used to obtain a signal proportional to $|u(t)|^2$ at the filter output, thus preserving the synchronism.

A schematic of the complete set-up is shown in Fig. 1. The laser used in the experiments is a commercially available, fiber pigtailed, 2.5 Gb/s, 1540 nm Distributed Feedback (DFB) laser (JDS Uniphase). A polarization controller is used to align the polarization of the GS DFB laser with the fixed linear polarizer. Before entering the interferometer, the signal is amplified by an erbium doped fiber amplifier (EDFA). The amplifier plays a double role in our experiments: it improves the signal to noise ratio and allows the measurement of the interferometer transfer function by using its amplified spontaneous emission (ASE) as input signal. The output of the interferometer is divided by a 50/50 coupler such that half of the signal is directed to an optical spectrum analyzer (OSA) and half to a fast photodiode and oscilloscope (20 GHz bandwidth).

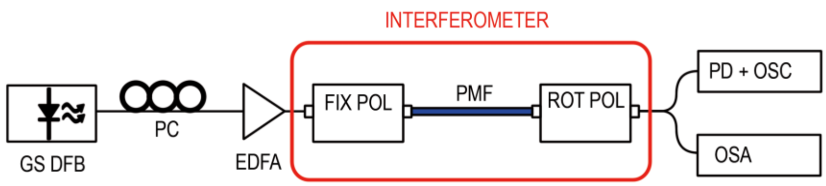

Fig. 1. Schematic of the experimental set-up consisting of: GS DFB laser, polarization controller (PC), EDFA, fixed linear polarizer (FIX POL), polarization maintaining fiber (PMF), rotatable linear polarizer (ROT POL), photodiode (PD), oscilloscope (OSC) and OSA.

Our interferometer is based on a birefringent medium, in a similar way to those previously used for other applications [25,26]. It consists of (i) one linear polarizer oriented at 45° with respect to the slow and fast axes of a polarization maintaining fiber (PMF), (ii) the PMF and (iii) a rotatable linear polarizer with variable polarization angle β, measured with respect to the slow axis of the PMF. The two orthogonal components of the light at the exit of the first polarizer travel different optical path lengths in the PMF due to the difference of the effective refractive index of the two axes of the fiber. Thus, the PMF axes act like the two arms of a Mach-Zehnder (MZ) interferometer. The out-coming components along the slow and fast axis of the PMF interfere at the rotatable polarizer with maximum contrast when the polarizer is oriented at 45° with respect to the PMF axes. By rotating the polarizer, the spectral response of the interferometer can be modified, to obtain a plain transfer function when its axis is aligned with the slow or fast axis of the PMF ($\beta = 0°$, $\beta = 90°$).

Figure 2 a) shows the GS laser spectrum, together with the magnitude of the interferometer transfer function as obtained by using the ASE spectrum of the EDFA as input signal and setting the rotatable polarizer with $\beta = 45°$. In the described set-up, the PMF length is 90 cm and the measured spectral half period (wavelength spacing between adjacent zeros) of the interferometer is 6.6 nm, corresponding to a temporal delay between the two interferometer arms of 1.2 ps, which yields an index difference between the PMF axes of about $4{\cdot}10^{-4}$. In our experiments the linear spectral filtering was ensured since the spectral full width half maximum (FWHM) for the most chirped pulse was 0.16 nm. As it can be observed in Fig. 2 a), the condition $|\Delta\omega| > |\omega_i(t)|$ is fully achieved, and a zero of transmission is close to the laser emission wavelength.

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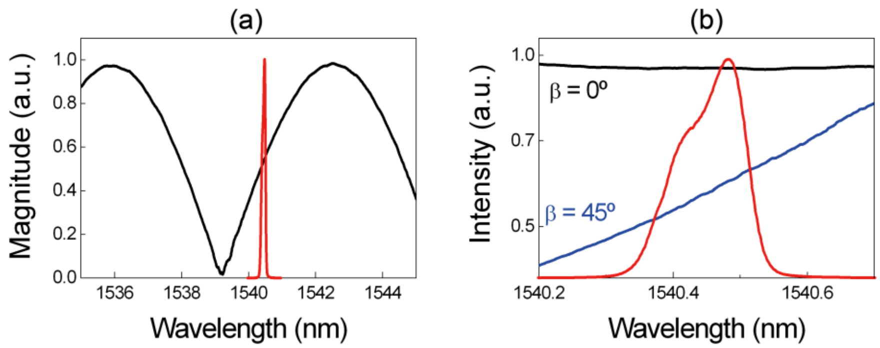

Fig. 2. (a) Measured magnitude of the interferometer transfer function for β = 45° (black line) and GS laser spectrum (red line). (b) Measured ASE spectra for β = 0° (black line) and β = 45° (blue line) and GS laser spectrum (red line).

The parameters A and $\Delta\omega$ of Eq. (1) are obtained from the linear fit of the ratio between the ASE spectra when β = 45° (maximum contrast) and β = 0° (plain spectrum). Figure 2 b) shows the measured ASE spectrum for β = 0° and β = 45° and the spectrum of the most chirped pulse in our experiments. The values obtained for A and Δω are $7.8{\cdot}10^{-13}$ s/rad and $1.0{\cdot}10^{12}$ rad/s, respectively.

3. Results and discussion

The optical pulses were generated with the GS DFB laser through the superposition of a bias current I_{BIAS} and a sinusoidal current with frequency 500 MHz and electrical power 4 dBm. The peak power at the laser output was ~0.7 mW. Three values of I_{BIAS} were used, resulting in pulses with different durations and shapes: I_{BIAS} = 13 mA, 16 mA and 20 mA (the laser threshold current is 13.6 mA). Figures 3 a), b) and c) show the measured intensities $|u(t)|^2$ and $|v(t)|^2$, and the corresponding instantaneous frequency calculated from Eq. (1) for the three pulses. The measured and reconstructed pulse spectra are shown in Figs. 3 d), e) and f). The pulse spectrum was reconstructed from the measured pulse intensity and the recovered phase by means of a discrete Fourier transform algorithm. The recovered spectra were convoluted with the measured spectral response of the OSA filter (the FWHM is 6.25 GHz), in order to be properly compared with the measured spectra.

The three measured pulses show frequency oscillations during the relaxation oscillations at the laser turn-on due to the carrier induced index modulation, typical of GS laser pulses [1]. By increasing I_{BIAS}, longer pulses and multiple spikes are observed at the output of the laser, producing double and triple peaked pulses.

The pulse obtained with I_{BIAS} = 13 mA, Fig. 3 a), has a FWHM duration of 102 ps. Its chirp decreases almost linearly along the pulse peak. This negatively chirped character is a consequence of the carrier induced index modulation resulting from the decrease of the carrier density during the first spike of relaxation oscillations. At the maximum pulse intensity, the carrier density crosses its threshold value, and consequently the instantaneous wavelength is that of the laser above threshold (neglecting thermal effects and assuming perfect carrier clamping above threshold). This fact has been used for a fine shift correction of the instantaneous frequency in Fig. 3.

The spectrum of the pulse obtained with I_{BIAS} = 13 mA is shown in Fig. 3 d). The pulse spectrum (FWHM ~20 GHz) shows an asymmetric profile with a shoulder on the positive frequency side, typical in GS laser pulses [27,28]. A very good agreement is obtained when comparing the reconstructed and measured spectra. This agreement is indicative of the validity of the time-resolved chirp measurements and hence of the capability of the implemented technique for chirp characterization of GS laser pulses.

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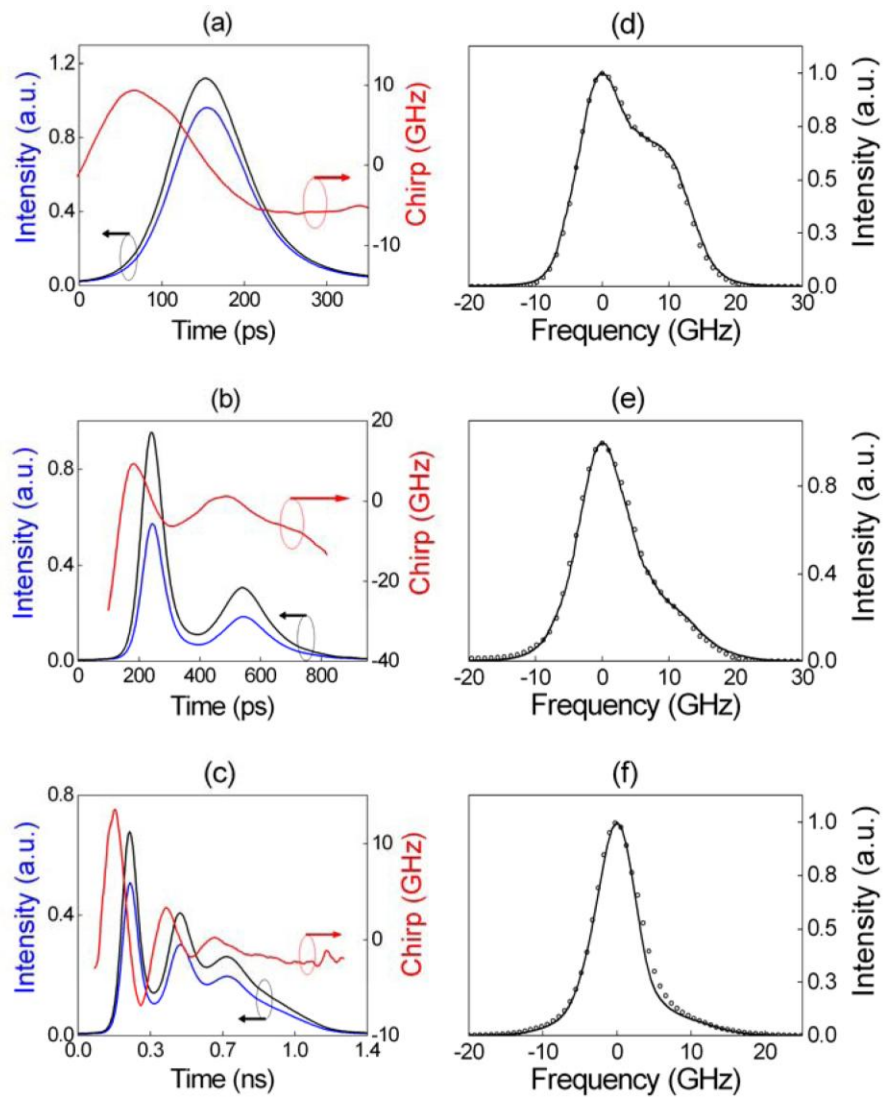

Fig. 3. Measured pulse intensities $|u(t)|^2$ (left, black lines) and $|v(t)|^2$ (left, blue lines), recovered instantaneous frequency (left, red lines), measured spectral profiles (right, black line) and recovered spectra (right, circles), for I_{BIAS} = 13 mA (top), 16 mA (centre), and 20 mA (bottom).

The pulse in Fig. 3 b), obtained for I_{BIAS} = 16 mA, has a total duration of 480 ps (at 13% of the maximum) and shows two intensity peaks with a temporal delay of 300 ps, corresponding to a relaxation oscillation frequency of 3.3 GHz. The recovered spectrum of this pulse has a fringed structure with fringe spacing equal to the inverse of the temporal delay between the two peaks. This fine spectral structure is washed out in the measured and in the recovered convoluted spectra due to the OSA finite resolution, as shown in Fig. 3 e).

A triple peaked pulse with total duration of 880 ps (at 13% of the maximum) and peak-spacing of 240 ps is obtained for I_{BIAS} = 20 mA, see Fig. 3 c). Increasing I_{BIAS} corresponds to an increase of the relaxation oscillation frequency and thus a reduction of the temporal delay between adjacent pulse spikes. The measured and reconstructed spectra (Fig. 3 f) show a more symmetrical profile and smaller spectral width than previous pulses, as a consequence of its longer duration.

#144483 - $15.00 USD Received 18 Mar 2011; revised 30 Apr 2011; accepted 12 May 2011; published 18 May 2011

The accuracy of the proposed technique for TRC characterization can be estimated from the comparison between the measured and recovered spectra. We define an error parameter ε as:

$$\varepsilon = 100 \cdot \frac{\int \left| I_m(\omega) - I_r(\omega) \right| d\omega}{\int I_m(\omega)\, d\omega}. \tag{2}$$

where $I_m(\omega)$ and $I_r(\omega)$ are the measured and the recovered intensity spectra, respectively, and the integrals extent over the entire pulse spectrum . The values of the error for the three measured pulses in Fig. 3 a), b) and c) are 3.9%, 6.3% and 7.1%, respectively. These errors correspond to an uncertainty in the chirp amplitude between 5 and 10%, as estimated by numerical simulation of the spectra, indicating that the accuracy of the measurement is better than 10%. This small error indicates that our implementation of PROUD technique is valid for the characterization of pulses generated from GS semiconductor lasers, avoiding the need of a high resolution spectrometer to apply phase reconstructions algorithms. Numerical simulations indicate that a spectral resolution better than 0.01 nm would be required to get similar errors by retrieving the phase from the temporal and spectral intensities.

The final resolution of our technique is limited by the signal to noise ratio of the temporal intensities. In our experiments the main source of noise is the timing jitter caused by the stochastic fluctuations of the GS laser turn-on. The TRC results presented here were measured by averaging 150 times the intensity profiles and applying a low pass filter during the data processing to get rid of the high-frequency noise.

In comparison with previous implementations of PROUD [15,16], our technique avoids the need for the compensation of the temporal delay between the input and output pulses. This implies a reduced set-up and a simplified experimental procedure which only takes a few minutes to perform a complete TRC measurement. The PMF based interferometer has proven to be very stable with ambient temperature fluctuations, due to the fact that the two arms of the interferometer, i.e. the slow and fast axis of the fiber, share the same medium and therefore are affected by the same thermal changes.

In comparison with other techniques for the characterization of TRC [9–14], our procedure is very simple avoiding time consuming sensitive adjustments. In fact, our technique is similar to the discriminator technique proposed in refs [9–12], which are also based on the measurement of the temporal intensities after filtering the signal with different transfer functions. The main advantage of the PROUD method in comparison with these techniques is that the expression providing the frequency chirp takes into account not only the amplitude of the frequency response of the filter, but also its phase response, which gives rise to the term $d|u(t)|/dt$ in Eq. (1). In consequence, it provides a more accurate measurement in the case of low chirped pulses. In addition, our procedure can be implemented making use of standard instrumentation in a photonics laboratory, such as a sampling oscilloscope and an OSA, in addition to common optical components and a low-cost PMF patch-cord. The non-iterative algorithm used in PROUD allows for a very fast determination of the TRC through a simple processing of the measured data.

This technique can be applied to measure pulses of different duration by proper design of the interferometer free spectral range using shorter or longer PMF lengths. The main limitation for the characterization of short pulses (in the range of ps or lower) is the need of a high bandwidth oscilloscope, but this can be overcome by using temporal stretchers, with well known frequency response, to broaden the original pulse [16]. In addition, the characterization of short pulses at higher data rates will be limited by the degradation of the signal to noise ratio and by the jitter. Further work is in progress to test the applicability of the method to directly modulated laser sources at higher data rates.

The proposed implementation of PROUD could be further improved for better performance and alternative applications. A balanced temporal PROUD [29,30] can be

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implemented by replacing the rotatable polarizer in Fig. 1 by a polarizing beam splitter, which, when properly aligned with respect to the PMF, would provide two outputs equivalent to the outputs of a conventional MZ interferometer. The temporal difference between the two outputs, measured by means of a balanced photodetector, is proportional to the input intensity and to the frequency chirp. The reduction of jitter and noise achieved with the balanced detection would allow for real-time and single shot TRC measurements. Furthermore, this balanced set-up could be used as demodulator of phase modulated optical signals to recover the instantaneous phase profile, in a similar manner to the balanced PROUD set-up based on a MZ interferometer [25].

4. Conclusions

We report the implementation of a simple, fiber based set-up for the direct measurement of the TRC in telecommunication optical signals. The instantaneous frequency is recovered from the temporal intensity of the pulse after temporal differentiation with a fiber based polarization interferometer, which is implemented with a PMF patch-cord and two linear polarizers. Our set-up avoids the temporal delay compensation needed in previously reported implementations of PROUD simplifying the experimental apparatus.

As a proof-of-concept the technique has been applied to characterize the TRC of a GS DFB laser emitting at 1540 nm. Single peaked and multi peaked pulses with durations ranging from 100 ps to 880 ps were measured. This is the first time, as far as we know, that phase recovery by optical differentiation is applied to the characterization of the carrier induced frequency modulation occurring during the relaxation oscillations in a directly modulated semiconductor laser. The spectra calculated from the measured intensity and the recovered phase were compared with the measured spectra, indicating that the error in the TRC is lower than 10%.

In comparison with other techniques for the complete characterization of optical signals our implementation has clear advantages regarding simplicity and accuracy. Moreover, it can be further improved for single shot real time characterization of phase modulated signals.

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