Simple Amplitude and Phase Measuring Technique for Ultrahigh-Repetition-Rate Lasers

P. Kockaert, M. Peeters, S. Coen, Ph. Emplit, M. Haelterman, and O. Deparis

***Abstract*—A simple method for the full amplitude and phase characterization of the light emitted by continuous-wave ultrahigh-repetition-rate lasers is experimentally demonstrated. The method is based on the measurement of the beat notes obtained by filtering pairs of adjacent longitudinal laser modes in a high-resolution, zero-dispersion grating-lens spectroscope arrangement. The method only requires the use of a simple fast photodiode and does not involve any nonlinear optical process.**

***Index Terms*—Gratings, laser measurements, optical pulse measurements, pulsed lasers.**

THE ADVENT of ultrahigh-capacity optical telecommunication networks has naturally called for the development of ultrahigh-repetition-rate laser sources. To match the channel bandwidth of current fiber links, these sources must emit picosecond pulses at repetition rates in the GHz range. Such laser sources are commonly characterized through their optical spectrum and their pulse duration T_0 usually obtained from a fast photodiode (typically if $T_0 > 20$ ps) or an autocorrelator (if $T_0 < 20$ ps). This approach does not yield any information regarding the exact shape and chirp profile of the pulses and consequently does not offer the possibility to study in detail the pulse generation processes. Yet, progress in the development of ultrahigh-repetition-rate laser sources relies on the knowledge of these processes. From this point of view, complete characterization techniques for such laser sources appear to be essential tools for the development of modern optical telecommunication systems.

Several methods for the complete amplitude and phase characterization of optical pulses have been reported in the literature of this last decade. Among them one finds the frequency-resolved optical gating (FROG) [1], the spectral phase interferometry (SPIDER) [2] and the direct optical spectral phase measurement (DOSPM) [3]. These three techniques are based on the use of optical nonlinearities and thus require high peak powers. They are therefore intrinsically unsuitable for the study of telecommunication laser sources. Following the pioneering conceptual work of Wong and Walmsley [4], two alternative methods have been implemented that do not employ optical nonlinearities [5]. However, these previous methods are rather complex in that they involve elaborate optical schemes including, for instance, optical cross-correlators, interferometric arrangements and/or a specially designed photodiode/microwave detector.

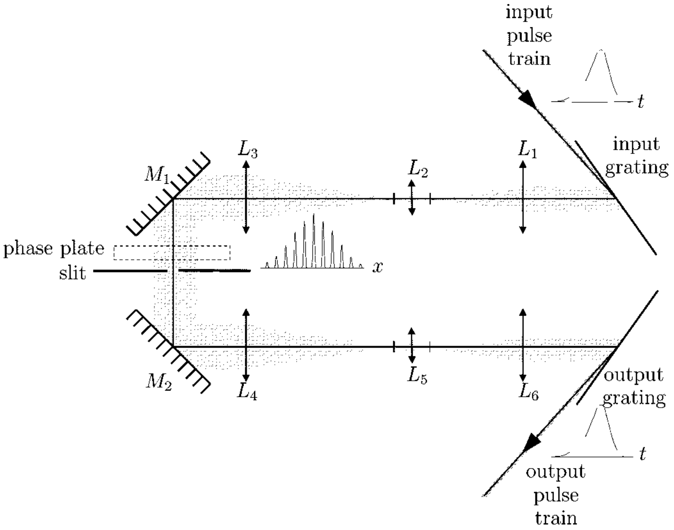

Fig. 1. Experimental setup. L_{1-6}: lenses, $M_{1,2}$: mirrors. The removable phase plate introduces a π-phase shift in one half of the spatially dispersed discrete spectrum.

In this letter, we present a simple pulse amplitude and phase characterization method that is intrinsically adapted to the high repetition rates of the telecommunication laser sources. Our method consists of an adaptation of the DOSPM technique to the analysis of periodic picosecond pulse trains. Its principle of operation can be described as follows. The high-resolution symmetric double grating-lens spectroscope arrangement depicted in Fig. 1 gives access to the discrete spectrum corresponding to the longitudinal modes of the laser under study. A single slit is placed in the Fourier plane to filter out two adjacent laser modes at a time. The resulting beat notes are measured by means of a fast photodiode (bandwidth $\simeq 50$ GHz) and an oscilloscope (bandwidth $\simeq 25$ GHz). The phases of the beat notes recorded on the oscilloscope for all the slit positions correspond to the phase differences between all adjacent modes and thus directly provide the spectral phase profile of the laser pulses. In terms of the laser repetition rate, the lower limit of the method is given by the resolution of the spectroscope arrangement that determines the minimum detectable laser mode frequency separation (typically a few GHz). The upper limit is given by the bandwidth of the detection system that

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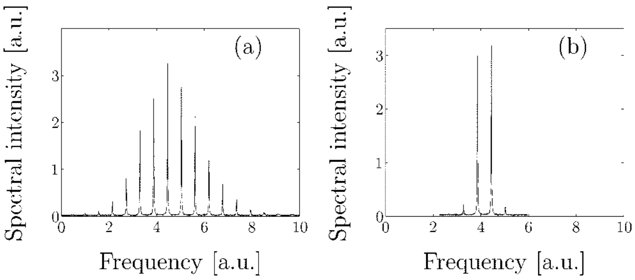

Fig. 2. (a) Discrete spectrum of the laser source under study as measured by a scanning Fabry–Perot interferometer, (b) an example of adjacent mode pair selected by the slit in the Fourier plane of the setup.

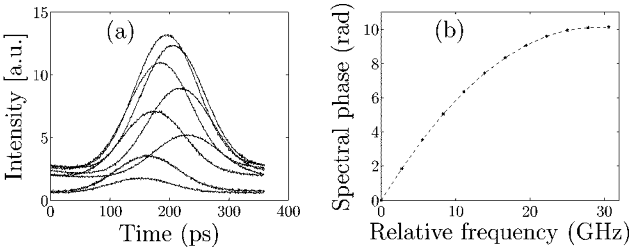

Fig. 3. (a) Examples of beat-note traces measured with the fast photodiode for different positions of the filtering slit in the absence of the phase plate. (b) Fig. 4. Reconstructed phase profile from the beat-note measurements of (a) and (3).

is in our case determined by the oscilloscope (25 GHz). The method appears therefore to be well suited to the study of modern telecommunication laser sources.

In order to illustrate the method, we have performed the characterization of an external-cavity mode-locked semiconductor laser. This laser emits 70 ps pulses at a repetition rate of $f_r = 2.78$ GHz. Fig. 2(a) shows its discrete optical spectrum measured by means of a Fabry-Perot interferometer. The corresponding temporal signal can be written as

$$E(t) = \sum_{n=0}^{N} A_n \exp(i\varphi_n) \exp(in\Omega t) \tag{1}$$

where n is the mode order ($n = 0$ being the first detectable mode of the series) and $\Omega = 2\pi f_r$.

To filter the laser longitudinal modes selectively, we built the high-resolution grating-lens spectrometer depicted in Fig. 1. This setup is peculiar in that it includes a telescope arrangement in order to magnify the Fourier plane so as to be able to filter selectively the laser longitudinal modes by means of a standard micrometric slit. In our setup, the distance between adjacent modes in the magnified Fourier plane is 280 μm. The slit width is fixed at around 300 μm so as to let two adjacent modes pass through it at a time. As shown in Fig. 1, after the slit the light goes through the same (symmetric) grating-lens arrangement so that the modes are recombined to generate a 2.78-GHz beat note at the system output.

Fig. 2(b) shows an example of filtered laser spectrum. The beat notes corresponding to each such pair of adjacent modes are measured by means of a fast photodiode and are recorded on a digital oscilloscope. Fig. 3(a) shows a set of recorded traces (note that, since we are only interested in the time variations, each trace is plotted with an arbitrary intensity scale and offset). The oscilloscope is triggered on the mode-locker radio-frequency signal which constitutes our time reference. As can be seen, the maxima of the beat notes do not occur at the same time, which shows that the phase difference between two adjacent modes varies across the spectrum and therefore reveals the presence of a spectral chirp. The corresponding spectral phase profile can be reconstructed very simply by measuring the phases of the recorded beat notes. This is performed automatically with a high accuracy by means of a least-mean-square fit algorithm. For each trace the fit is performed with the function $A\cos(\Omega t + \phi_n)$. The value of the beat-note phase ϕ_n given by the algorithm for each trace provides the phase differences of the corresponding pair of adjacent modes, i.e., $\phi_n = \varphi_{n+1} - \varphi_n$. This fit algorithm has the advantage of providing a result that is not influenced by the higher order harmonics present in the traces [as is visible in Fig. 3(a)] due to the limited filtering resolution that let additional adjacent modes pass through the slit [see Fig. 2(b)]. However, the additional adjacent modes also contribute to the fundamental harmonic through the beating with their first neighbors. This is the major source of inaccuracy in our method. The corresponding error can be easily evaluated *a posteriori* from the measurement of the additional harmonic amplitudes and phases. For the example of Fig. 3(a) one finds a relative error on the phase measurement that does not exceed a few percent.

It is important to note that the traces are recorded with an arbitrary but fixed trigger time. In order to determine the pulse amplitude and chirp profile, there is no need to know this trigger time. The phase differences are simply given with the same unknown constant, say Ψ, and can thus be written as

$$\Delta\varphi_n = \varphi_{n+1} - \varphi_n + \Psi. \tag{2}$$

With this notation, it is easy to show that (1) can be reformulated as

$$E(t) = \sum_{n=0}^{N} A_n \exp(i\Phi_n) \exp[in\Omega(t - \Psi/\Omega)] \exp(i\varphi_0) \tag{3}$$

where

$$\Phi_n = \sum_{k=0}^{n-1} \Delta\varphi_k = \varphi_n - \varphi_0 + n\Psi. \tag{4}$$

This expression shows that the field envelope $E(t)$ can be reconstructed from the measurement of the beat-note phases $\Delta\varphi_n$ and the mode amplitudes A_n that are measured separately by means of a standard scanning Fabry–Perot interferometer. The only effect of the unknown phase Ψ is to introduce a spectral phase slope corresponding, in the temporal domain, to a displacement of $\Delta t = \Psi/\Omega$ as is explicit in (3). The laser pulse spectral phase profile Φ_n, as reconstructed from (4), is represented in Fig. 3(b). As can be seen from the parabolic shape of the curve, a chirp is present in the spectrum showing that the pulses are not Fourier-transform limited.

In Fig. 4, we plotted the reconstructed temporal intensity envelope as obtained from (3). The response time of the photodiode is 11.5 ps which, compared to the 70-ps duration of the

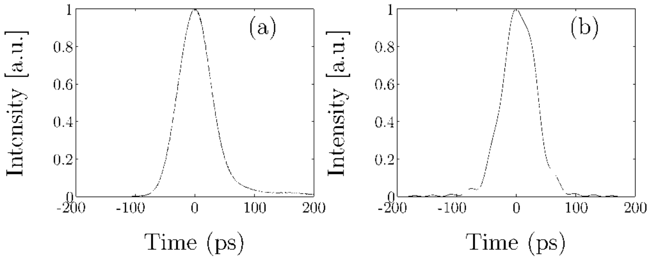

Fig. 4. (a) Pulse intensity profile measured with the fast photodiode. (b) Pulse intensity profile reconstructed from (3) with the mode amplitudes of Fig. 2(a) and the beat-note measurements of Fig. 3(a).

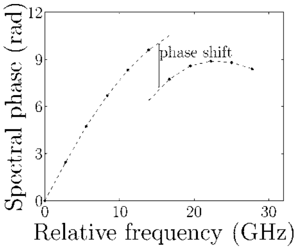

Fig. 5. Reconstructed phase profile in the presence of the π-phase plate in the Fourier plane of the filtering setup.

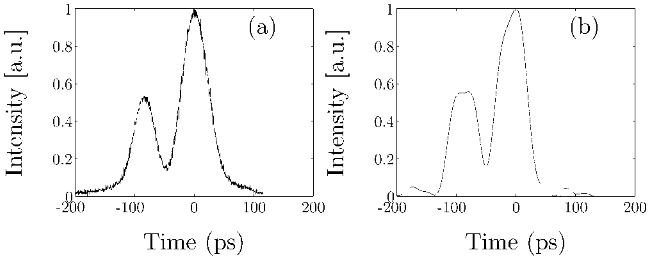

Fig. 6. Pulse intensity profile in the presence of a π-phase plate in the Fourier plane in the conditions of Fig. 5. (a) Intensity profile measured with the fast photodiode. (b) Intensity profile reconstructed from (3).

pulses, provides a temporal measurement of relatively good accuracy. We observe in Fig. 4 that the reconstructed profile is in good agreement with the direct intensity measurement. The slight oscillations visible in the wings of the reconstructed pulse are due to the fact that the method does not allow us to consider the modes of low intensity in the wings of the spectrum because of their low signal-to-noise ratio. Note that in the application of our method we have to assume that the pulse train is purely periodic. If there were fluctuations from pulse to pulse, the measurement would only provide an average pulse profile. In that case the averaging must be seen as a source of limitation of the accuracy of the method.

In order to further test our method we applied it to the measurement of highly chirped pulses. The chirp is introduced in the laser pulses by placing a phase plate within the Fourier plane of the grating-lens spectroscope arrangement (see Fig. 1). The phase plate is profiled so that it introduces a π-phase shift in one half of the spectrum. The spectrum thus exhibits a strong phase discontinuity that is expected to lead to a strong distortion of the temporal pulse profile. Fig. 5 shows the resulting phase profile. The π-phase jump between the two halves of the spectrum is clearly visible. Fig. 6 shows the reconstructed intensity profile and the direct temporal measurement. The agreement between both profiles reveals the reliability of the method.

In conclusion, we have presented an original method for the full amplitude and phase characterization of the signal emitted by telecommunication-dedicated laser sources. The method consists of an adaptation of the DOSPM technique to the low powers and high repetition rates of these laser sources. Its originality lies in the fact that it exploits the discreteness of the spectrum associated with the periodicity of the emitted signals. This allows for the use of a single standard micrometric slit for the spectral filtering that is at the basis of the signal analysis. Another advantage of the method is that signal detection is performed by means of a simple fast photodiode and therefore does not require any nonlinear optical process. As regards the discrete spectrum analysis approach as well as the absence of any nonlinear process, our method can be compared to that recently proposed by Debeau *et al.* in [6]. In that method, the discrete optical spectra of ultrahigh-repetition-rate lasers are analyzed after signal modulation with a variable delay in an integrated electrooptic Mach–Zehnder interferometer. With respect to that previous technique, our method has the advantage of requiring only a very simple and standard Fourier optics equipment.

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