Pulse Characterization at 1.5 μm Using Time-Resolved Optical Gating Based on Dispersive Propagation

Roger G. M. P. Koumans and Amnon Yariv

***Abstract*—This letter demonstrates the use of time-resolved optical-gating-based on dispersive propagation to characterize a semiconductor mode-locked laser emitting picosecond pulses at a wavelength of 1.5 μm. DP-TROG is a new noninterferometric method for characterizing ultra-short optical pulses in amplitude and phase without the need for a short optical gating pulse. We describe and give recommendations for the reconstruction of the pulse properties from the set of measured autocorrelation traces and the intensity spectrum.**

***Index Terms*—Optical correlators, optical pulse compression, optical pulse measurements, pulse characterization.**

OVER the last few years the number of methods to characterize optical pulses has grown rapidly. Debeau recently introduced a linear method to characterize the pulse shape [1]. Although this method offers a simple solution without an iterative algorithm, it requires external modulation and electrical synchronization of the pulse train which is not always available especially in the case of high pulse repetition rates. We recently introduced and theoretically investigated the technique of time resolved optical gating based on dispersive propagation (DP-TROG) to characterize optical pulses [2]. Although there are other techniques that employ dispersion and *cross correlation* with a short gate pulse to characterize a pulse [3], our technique measures the *autocorrelation* trace of the dispersed pulse and does, therefore, not require a short gate pulse. The TROG technique is similar to frequency-resolved optical-gating (FROG) [4] except that the role of time and frequency is interchanged. In TROG the pulse properties are derived with a similar iterative algorithm as in FROG. For more details on the duality between TROG and FROG the reader is referred to [2]. Compared to FROG based on second harmonic generation (SHG), the DP-TROG technique does not have an ambiguity in the direction of time for the pulse and although DP-TROG is not a single-shot measurement, it has a power advantage over FROG as the SHG does not need to be spectrally resolved.

This paper describes the experimental demonstration of the DP-TROG technique to characterize a pulse train emitted from a 2 mm long two-section mode-locked semiconductor laser at a wavelength of 1.5 μm. The absorber section of the laser is 100 μm long and is grounded while the gain section is pumped at a current of 170 mA. The pulses are amplified by an erbium-doped fiber amplifier (EDFA) after which they enter the measurement setup shown in Fig. 1. The pulse to be characterized, with slowly varying complex envelope $A(t)$, first enters a dual grating telescope disperser [5]. The disperser ads a spectral phase to the pulse which is quadratic in frequency. The Fourier transform of the pulse leaving the disperser is

$$\tilde{A}'(f, D) = \tilde{A}(f) \exp(j\pi f^2 D) \tag{1}$$

where $D(z) = -2\pi\beta_2 z$ is the amount of dispersion added to the pulse which can be varied by adjusting the distance z between the grating and the focal point of the telescope. The effective

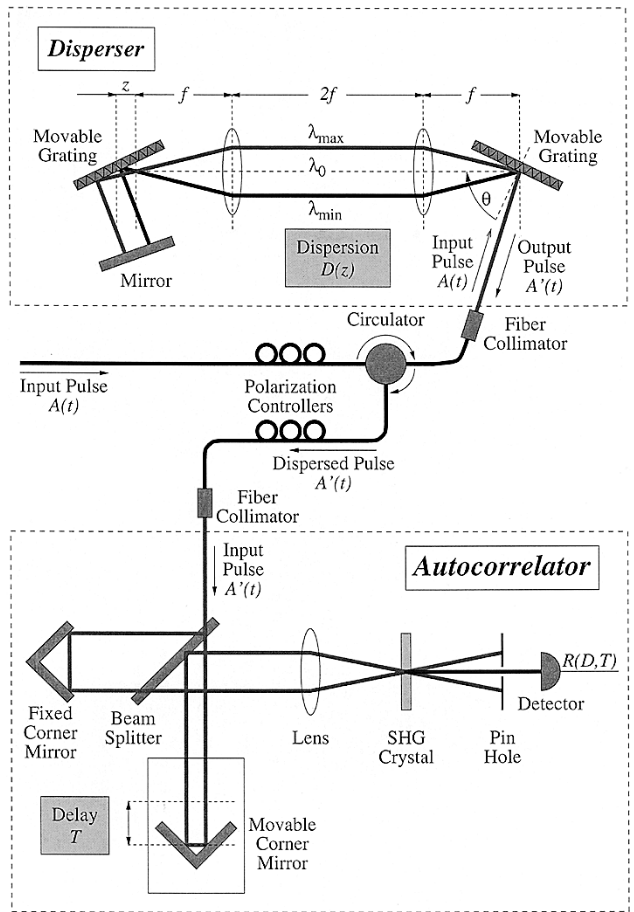

Fig. 1. DP-TROG measurement setup consisting of a dual grating disperser and a background-free autocorrelator.

Manuscript received September 27, 1999; revised January 17, 2000. This work was funded by the Defense Advanced Research Projects Agency and the Office of Naval Research.

The authors are with the California Institute of Technology, Department of Applied Physics, Pasadena, CA 91125 USA (e-mail: koumans@its.caltech.edu).

Publisher Item Identifier S 1041-1135(00)04589-4.

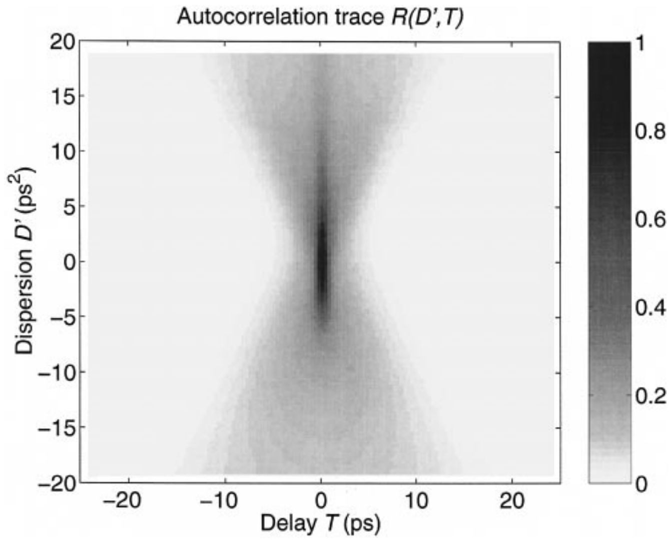

Fig. 2. Two-dimensional view of the set of measured autocorrelation traces $R(D', T)$.

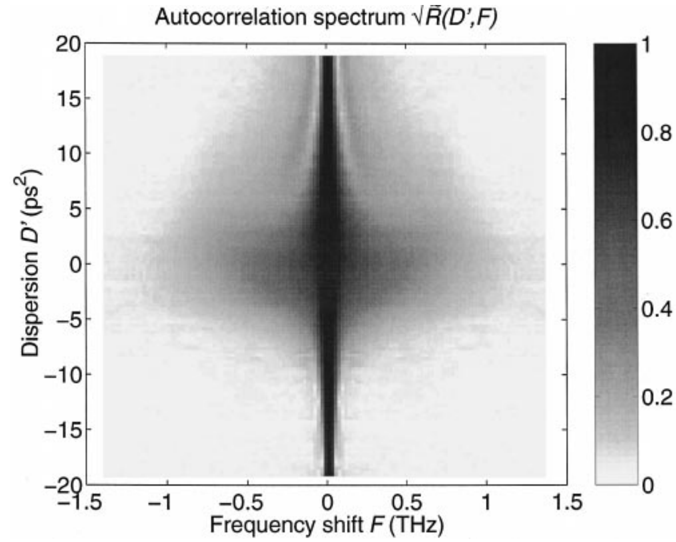

Fig. 3. Autocorrelation spectrum $\sqrt{\tilde{R}(D', F)}$ obtained by Fourier transformation of the autocorrelation traces of Fig. 2 with respect to T.

dispersion parameter β_2 of the dual grating telescope is given by [5]

$$\beta_2 = \frac{-\lambda_0^3}{\pi c^2 d^2 \cos^2 \theta} \tag{2}$$

where the following experiment values are used: $\lambda_0 = 1539$ nm is the center wavelength of the pulse, c is the speed of light in vacuum, $1/d = 830$ mm^{-1}is the grating line density and $\theta = 79.5°$ is the angle between the normal to the grating and the telescope axis. The total insertion loss of the disperser is approximately 10 dB.

The pulse $A'(t)$ leaving the disperser is a compressed/stretched version of the input pulse $A(t)$ depending on the amount of dispersion D added. This pulse next enters a background-free autocorrelator in which its second harmonic is measured as a function of the autocorrelator delay T. The resulting set of autocorrelation traces $R(D, T)$ is given by

$$R(D, T) = \int |A'(t, D)|^2 |A'(t - T, D)|^2 \, dt. \tag{3}$$

We measure a number of autocorrelation traces around the dispersion point D_0 for which maximum pulse compression occurs (i.e., minimum autocorrelation width). For each trace the distance z is incremented by $\Delta z = 0.2$ mm. The measured traces $R(D, T)$ are normalized to the same energy and are next mapped onto an $N \times N$ grid with $N = 128$ and with dispersion step $\Delta D = 0.3$ ps^2 and time step $\Delta T = 0.36$ ps. A two-dimensional top view of the measured traces $R(D', T)$ is shown in Fig. 2 where $D' = D - D_0$ and $D_0 = 16$ ps^2. In addition to this, the intensity spectrum of the pulse is also measured.

We now follow the pulse reconstruction procedure for the *compressed* pulse as described in [2]. We first calculate $\tilde{R}(D', F)$, the Fourier transform of $R(D', T)$ with respect to T. The result is shown in Fig. 3. In order to enhance the noise features in this trace we have plotted its square root. We next transform this trace into the DP-TROG trace [2]

$$I(T, F) = \left| \int \tilde{A}(f) \tilde{A}^*(f - F) \exp(j 2\pi f T) \, df \right|^2 \tag{4}$$

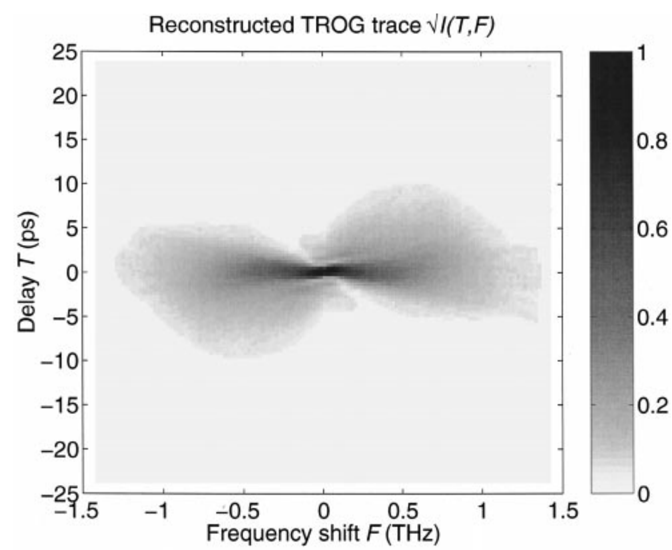

Fig. 4. Reconstructed DP-TROG trace after interpolation and noise filtering.

by evaluating the trace $\tilde{R}(D', F)$ at points $(T_i/F_j, F_j)$. The trace with $F = 0$ cannot be evaluated in this way but is constructed from the measured intensity spectrum of the pulse. In order to speed up and improve algorithm convergence we interpolate the resulting trace in the F-direction as described in [2]. We next apply a noise reduction technique to the DP-TROG trace to limit the influence of additive noise on the pulse reconstruction. Several techniques for noise reduction have been discussed previously [6]. We use a median threshold filtering technique. In determining whether to keep the value of a pixel in the trace or set it to zero, we determine the average pixel value over a square of size $2p+1$ around the pixel of interest. If this average pixel value is smaller than a certain threshold s, we set the current pixel to zero. Our noise filtering technique uses the values $p = 2$ and $s = 1.5 \cdot 10^{-3}$. The resulting filtered DP-TROG trace is shown in Fig. 4. This trace is next used as input to the pulse reconstruction algorithm [2]. The amplitude and phase of the retrieved compressed pulse in the frequency- and time-do-

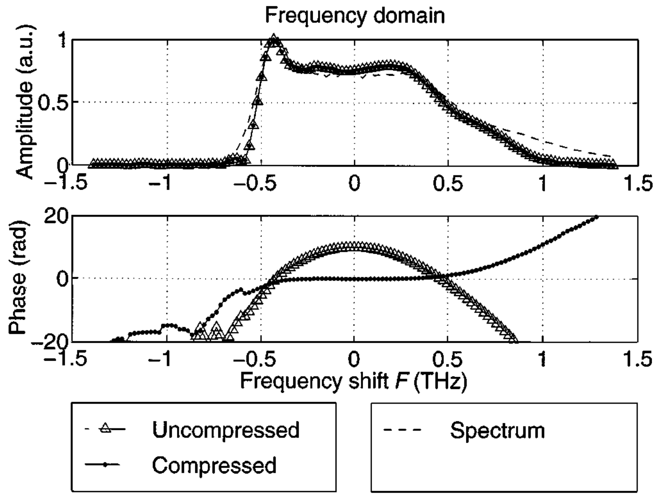

Fig. 5. Amplitude and phase represented in the frequency-domain: compressed pulse (dots) and original uncompressed pulse (triangles). Also shown is the measured intensity spectrum of the pulse (dashed line).

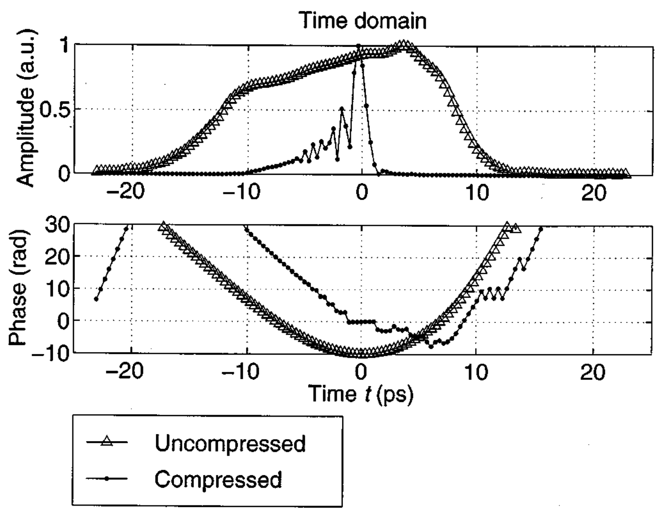

Fig. 6. Amplitude and phase represented in the time-domain: compressed pulse (dots) and original uncompressed pulse (triangles).

main are shown in Figs. 5 and 6, respectively (dots). The amplitude and phase profile of the original uncompressed pulse can be calculated from the retrieved compressed pulse by adding the amount of dispersion D_0 needed to get to the maximum compression point. Its results can also been seen in Figs. 5 and 6. We have also plotted the measured spectrum in Fig. 5. Agreement of the retrieved spectrum with the measured one is very good. From Fig. 5, it can be clearly seen that the original uncompressed pulse contains a nonlinear chirp. The linear part of the chirp can be compensated by adding an amount of dispersion D_0. The resulting compressed pulse has a residual cubic spectral phase dependence. Upon transformation to the time-domain this cubic phase causes ringing (phase jumps of π) on the leading edge of the pulse (see Fig. 6). As described in [2] interpolation of the TROG trace is not necessary for correct spectral *phase* retrieval. This is also true for our measurements. The spectral phase of the pulse is reconstructed correctly even if we omit the interpolation of the DP-TROG trace. Without the interpolation there is a larger error between the retrieved spectral amplitude and the measured one. This is, however, of no concern as the exact spectral amplitude is available from the measurement, and an accurate time-domain representation of the pulse can be obtained by using the spectral phase retrieved by the algorithm together with the measured spectral amplitude.

In this letter, we have not taken into account the effect of higher order dispersion introduced by the compressor. We are currently investigating this issue. For our setup, one can however calculate these higher order dispersions similar as in [7]. The cubic phase is around a few percent of the quadratic phase and does not lead to any pulse reconstruction difficulties. It is noted that a TROG trace contains redundant information and is therefore very stable against measurement noise and thus even though the exact dispersion value might be sligthly off from the measured one, the algorithm is still able to retrieve the correct pulse properties as long as these deviations are within a reasonable range (typically up to a few percent). More important for the measurement is the dispersion range over which measurements are made. Guidelines for this are given in [2]. In principle it is also possible with our setup to adjust the cubic and quartic phase by changing the azimuth angle of the gratings [7].

In conclusion, we have succesfully characterized an optical pulse with the DP-TROG technique. The pulse contains a nonlinear chirp whose linear part can be cancelled out by a disperser. The remaining nonlinear part causes ringing on the leading edge of the compressed pulse.

ACKNOWLEDGMENT

The authors would like to thank T.R. Chen for fabrication of the laser used in this work.

REFERENCES

[1] J. Debeau, B. Kowalski, and R. Boittin, "Simple method for the complete characterization of an optical pulse," *Opt. Lett.*, vol. 23, no. 22, pp. 1784–1786, 1998.
[2] R. G. M. P. Koumans and A. Yariv, "Time-resolved optical gating based on dispersive propagation: A new way to characterize optical pulses," *IEEE J. Quantum Electron.*, vol. 36, pp. 137–144, Feb. 2000.
[3] J. C. Diels, J. J. Fontaine, I. C. McMichael, and F. Simoni, "Control and measurement of ultrashort pulse shapes (in amplitude and phase) with femtosecond accuracy," *Appl. Opt.*, vol. 24, no. 9, pp. 1270–1282, 1985.
[4] R. Trebino, K. W. DeLong, D. N. Fittinghoff, J. N. Sweetser, M. A. Krumbugel, B. A. Richman, and D. J. Kane, "Measuring ultrashort laser pulses in the time-frequency domain using frequency-resolved optical gating," *Rev. Scientific Instrum.*, vol. 68, no. 9, pp. 3277–3295, 1997.
[5] O. E. Martinez, "3000 times grating compressor with positive group-velocity dispersion—Application to fiber compensation in 1.3–1.6 μm region," *IEEE J. Quantum Electron.*, vol. QE-23, pp. 59–64, Jan. 1987.
[6] D. N. Fittinghoff, K. W. DeLong, R. Trebino, and C. L. Ladera, "Noise sensitivity in frequency-resolved optical-gating measurements of ultrashort pulses," *J. Opt. Soc. Amer. B*, vol. 12, no. 10, pp. 1955–1967, 1995.
[7] C. M. G. Inchauspe and O. E. Martinez, "Quartic phase compensation with a standard grating compressor," *Opt. Lett.*, vol. 22, no. 15, pp. 1186–1188, 1997.