Available online at www.sciencedirect.com
SCIENCE DIRECT®
Optical Fiber Technology 10 (2004) 73–78
Optical Fiber Technology
www.elsevier.com/locate/yofte

Sensitivity of SHG-FROG for the characterization of ultrahigh-repetition-rate telecommunication laser sources

Julien Fatome, Stéphane Pitois, and Guy Millot *

Laboratoire de Physique de l'Université de Bourgogne, Unité Mixte de Recherche CNRS 5027, Faculté des Sciences Mirande, 9 Avenue A. Savary, B.P. 47870, 21078 Dijon, France

Received 6 January 2003; revised 5 July 2003

Abstract

We analyze experimentally the sensitivity of second-harmonic generation frequency-resolved optical gating (SHG-FROG) for the complete intensity and phase characterization of both a sinusoidal beat signal and a train of 1.3 ps pulses at a repetition rate of 160 GHz at 1550 nm. Using a commercially-available optical spectrum analyzer in the SHG-FROG set-up, incident pulses with energies of only 125 and 190 fJ, which correspond to the beat signal and the 1.3 ps pulse train, respectively, have been accurately characterized.

1. Introduction

In ultrafast telecommunication systems using optical time-division multiplexing, picosecond and subpicosecond optical pulses will be transmitted through optical fibers at repetition rates of several hundreds of Gbit/s [1]. However, chromatic dispersion and Kerr effects may cause severe distortions in the shape and chirp of the transmitted ultrashort pulses. Thus, the ability to measure the fundamental parameters of optical pulses as well as pulse distortions after propagation in a high-speed transmission line is of major importance for the optimization of input laser sources and the design of high-speed transmission lines.

* Corresponding author.
E-mail address: guy.millot@u-bourgogne.fr (G. Millot).

1068-5200/$ – see front matter
doi:10.1016/j.yofte.2003.08.001

In this context, the ultrashort pulse measurement technique of frequency resolved optical gating (FROG) is now a well-established method to retrieve intensity and phase of ultrashort pulses [2] and has been successfully applied in the third telecommunication window around 1550 nm, to characterize isolated single pulses from sources having repetition rates ranging from 4.2 MHz to 40 GHz [3–7]. In addition, FROG has been extended to allow the characterization of *periodic pulse trains* at ultrahigh repetition rates ranging from several hundreds of GHz to a few THz, although this work has, to date, been restricted to pulse trains in the visible with peak powers in the 100 W range [8]. Moreover, it has recently been shown that FROG inversion algorithms can accurately retrieve relatively elaborated optical fields such as that of a pseudo-random sequence of chirped pulses [9]. The FROG technique appears therefore as an essential tool for analysis of ultrahigh bit rates generation and transmission in modern telecommunication experiments.

However, to the best of our knowledge, FROG has not yet been applied to the characterization of pulse trains with ultrahigh repetition rates ($>$40 GHz) at telecommunication wavelengths. In this paper, we report the experimental characterization of 160 GHz pulse trains around 1550 nm with a FROG system based on second-harmonic generation (SHG) in a BBO crystal and a commercial optical spectrum analyzer. In particular, we study experimentally the sensitivity of SHG-FROG for the characterization of both a beat signal and a 1.3 ps pulse train. An important feature of our results when compared with single pulse characterization [3–7] is that the accurate characterization of ultrashort pulse trains allows the recovery of the phase jump between adjacent pulses.

2. SHG-FROG setup

Figure 1a shows the SHG-FROG setup based on the spectral analysis of the SHG autocorrelation signal using an optical spectrum analyzer (OSA, Anritsu MS9710B). The two time-delayed replicas of the input signal were focused (in a background-free geometry) in a 2 mm-thick BBO crystal by a 5 cm focusing lens. The bandwidth of the phase-matching efficiency for the crystal was estimated to be larger than 100 nm. A variable time delay between the two replicas was tuned by means of a step-motor controlled translation stage. A polarization controller was used to minimize the insertion loss of the polarizer placed at the autocorrelator input and to optimize the SHG signal. The FROG trace was conveniently built up by adjusting the autocorrelator to a particular delay, and then by scanning the OSA wavelength with a spectral resolution of 0.07 nm. The measured spectra were then interpolated onto a 256×256 grid, and used as input to the algorithm for the retrieval of the periodic pulse-train characteristics [8].

At this point, we discuss several features related to the definition of the sensitivity of an SHG-FROG setup. First let us recall that the sensitivity of an autocorrelator can be defined as the product of the peak and average powers of the incident pulse which is characterized ($P_{\text{average}} \times P_{\text{peak}}$). For an autocorrelator, this measure of sensitivity is widely-used because it is directly proportional to the integrated average power of the second harmonic autocorrelation signal at zero delay. However, in the case of an SHG-FROG setup, this measure is inappropriate because the SHG signal is spectrally resolved. As a result, a correct definition of the sensitivity of an SHG-FROG signal is significantly more complicated, as it must take

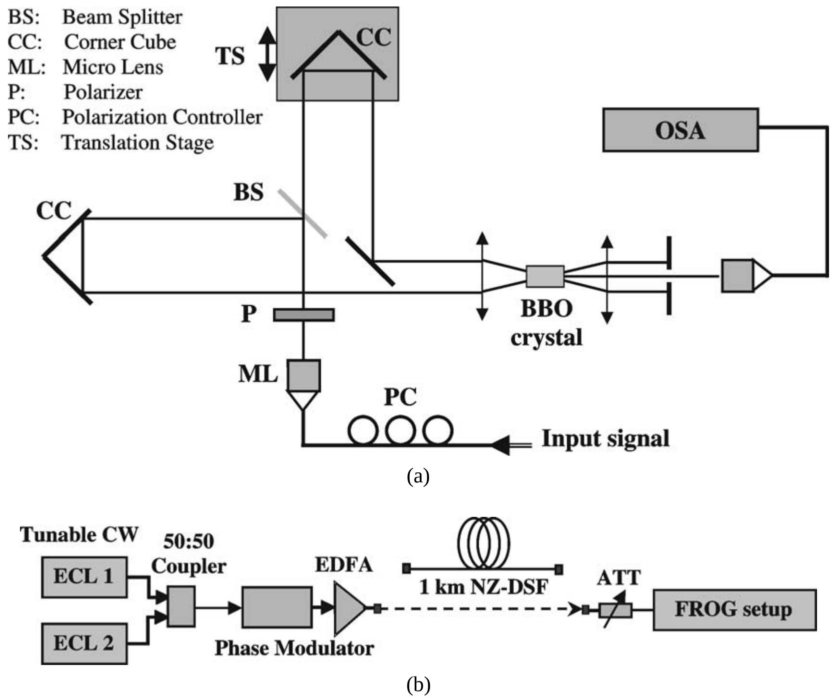

Fig. 1. Experimental setup: (a) SHG-FROG system, (b) pulse train generation at 160 GHz.

into account the different types of incident field and the particular type of spectral analysis which is being carried out, either using a fixed grating and CCD array, or a rotating grating and a fixed detector, but this is outside the scope of this paper.

3. Experimental results

3.1. 160-GHz sinusoidal beat signal

The first experiment that we carried out is the characterization of a sinusoidal beat signal at 160 GHz, with well-known intensity and phase, obtained from the superposition of two continuous waves centred around 1550 nm. Both waves were delivered by tunable external cavity lasers (ECL's) subsequently amplified by an Erbium amplifier, as shown in Fig. 1b. The two wave powers were set to the same value and the polarization states were aligned parallel. Figures 2a and 2b show the measured and the retrieved FROG traces of this beat signal, respectively. The total average power was fixed to 13 dB m at the input of the autocorrelator, which corresponds to a pulse (cycle) energy of 125 fJ. The retrieved intensity and phase, shown in Fig. 2c, exhibit the expected characteristics of a 100% modulated sinusoidal beat signal. The retrieval error was found to be $G = 0.011$. As can be seen in Figs. 2d and 2e, respectively, the excellent agreement between the experimental spectrum

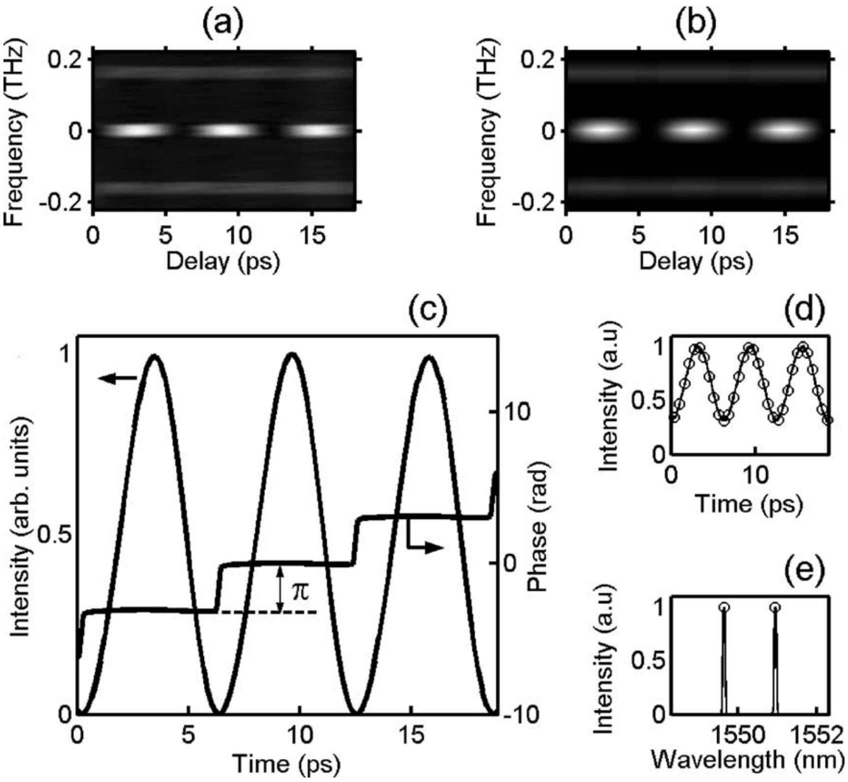

Fig. 2. Results for sinusoidal beat signal: (a) experimental SHG-FROG trace, (b) retrieved SHG-FROG trace, (c) retrieved intensity (left axis) and phase (right axis), (d) autocorrelation functions, (e) spectra calculated from the retrieved intensity and phase (○), and measured (–).

and autocorrelation function of the beat signal directly measured (solid line), and those calculated from the retrieved field (circles), confirms the reliability of our characterization system.

3.2. 160-GHz train of 1.3-ps pulses

Another series of experiments was carried out in order to characterize a 160-GHz train of 1.3-ps pulses. This pulse train was generated using multiple four-wave mixing temporal compression of a beat signal in the anomalous-dispersion regime [10,11] of a 1-km-long non-zero dispersion-shifted fiber (NZ-DSF). The beat-signal average power was set to 27.2 dB m. Stimulated Brillouin scattering in the NZ-DSF was suppressed by externally modulating the two ECLs with a phase modulator (see Fig. 1b). The NZ-DSF has 0.21 dB/km loss, an anomalous dispersion of 1 ps/nm/km, a nonlinear coefficient of 1.7 $W^{-1}\,km^{-1}$, and a third-order dispersion of 0.07 $ps/nm^2/km$. Figure 3 shows the results obtained when the average power of the compressed pulse train was fixed to 23 dB m at the input of the FROG setup. The retrieval error was $G = 0.0019$. Let us remark that the

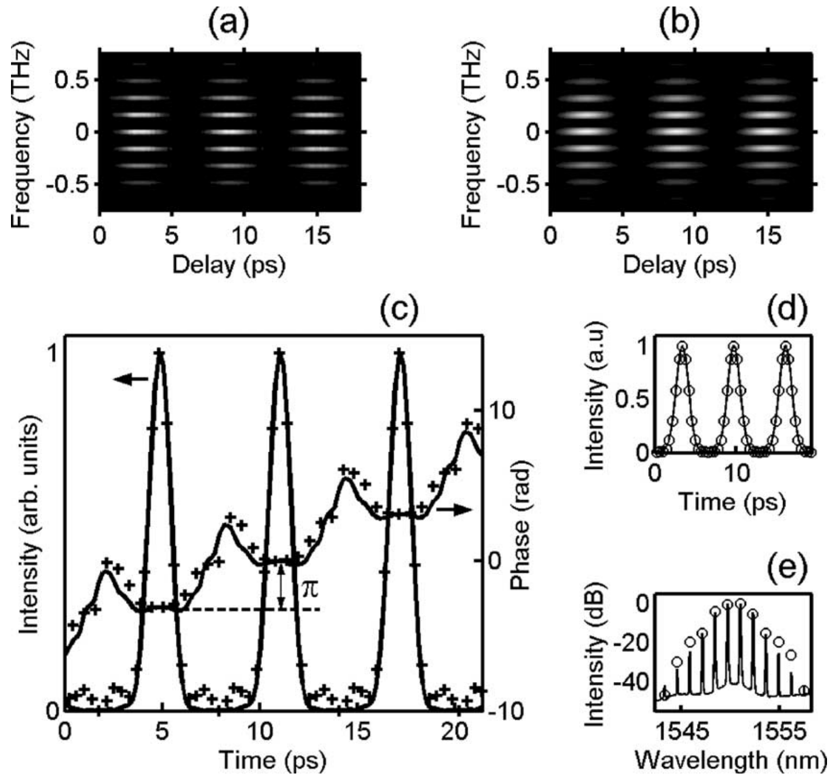

Fig. 3. As in Fig. 2 but for compressed pulse train.

intensity and phase profiles show compressed pulses without pedestal or chirp. Figure 3c (crosses) shows the retrieved intensity and phase obtained when the average power measured at the input of the FROG setup was decreased to 14.8 dB m, corresponding to a pulse energy of 190 fJ, and a peak power of 140 mW. The comparison between the 14.8 dB m (crosses) and the 23 dB m (solid line) results clearly shows that the shape and phase of the compressed pulses remain correctly retrieved at the lower power as confirmed by the corresponding small retrieval error $G = 0.007$.

4. Conclusion

In conclusion, we have shown that the SHG-FROG technique, employing commercially available BBO crystal and OSA, can accurately characterize 1550 nm-pulse trains at a repetition rate of 160 GHz with pulse energy (average power) less than 200 fJ (15 dB m). Our results represent the first experimental demonstration of the ability of SHG-FROG to characterize telecommunication laser sources operating at ultrahigh repetition rates (>40 GHz) and low average power.

Acknowledgments

The authors would like to thank Alcatel France for providing them the 1-km-NZ-DSF and H. Bissesur, P. Brindel, J.M. Dudley, P. Grelu, F. Gutty, and P. Tchofo-Dinda for fruitful discussions. This research was supported by the Conseil régional de Bourgogne, the Centre national de la recherche scientifique (CNRS), and the Ministère de la recherche under contract ACI Jeunes 2015. G.M. acknowledges financial support from the Institut Universitaire de France.

References

[1] M. Nakazawa, T. Yamamoto, K. Tamura, 1.28 Tbit/s—70 km OTDM transmission using third- and fourth-order simultaneous dispersion compensation with a phase modulator, Electron. Lett. 36 (24) (2000) 2027–2029.
[2] R. Trebino, K.W. Delong, D.N. Fittinghoff, J.N. Sweetser, M.A. Krumbugel, B.A. Richman, D.J. Kane, Measuring ultrashort laser pulses in the time-frequency domain using frequency-resolved optical gating, Rev. Sci. Instrum. 68 (9) (1997) 3277–3295.
[3] F.G. Omenetto, J.W. Nicholson, A.J. Taylor, Second-harmonic generation-frequency-resolved optical gating analysis of low-intensity shaped femtosecond pulses at 1.55 µm, Opt. Lett. 24 (23) (1999) 1780–1782.
[4] K. Taira, K. Kikuchi, Highly sensitive frequency-resolved optical gating in 1.55 µm region using organic nonlinear optical crystal for second-harmonic generation, Electron. Lett. 36 (20) (2000) 1719–1720.
[5] M.D. Thomson, J.M. Dudley, L.P. Barry, J.D. Harvey, Complete pulse characterization at 1.5 µm by cross-phase modulation in optical fibers, Opt. Lett. 23 (20) (1998) 1582–1584.
[6] P.A. Lacourt, J.M. Dudley, J.M. Merolla, H. Porte, J.P. Goedgebuer, W.T. Rhodes, Milliwatt peak power pulse characterization at 1.55 µm via wavelength conversion frequency resolved optical gating, Opt. Lett. 27 (11) (2002) 863–865.
[7] L.P. Barry, S. Del Burgo, B. Thomsen, R.T. Watts, D.A. Reid, J. Harvey, Optimization of optical data transmitters for 40-Gb/s lightwave systems using frequency resolved optical gating, IEEE Photon. Technol. Lett. 14 (7) (2002) 971–973.
[8] J.M. Dudley, M.D. Thomson, F. Gutty, S. Pitois, P. Grelu, G. Millot, Complete intensity and phase characterisation of optical pulse trains at terahertz repetition rates, Electron. Lett. 35 (23) (1999) 2042–2044.
[9] P. Grelu, F. Gutty, G. Millot, Pseudo-random pulse sequence characterization with frequency-resolved optical gating, IEEE Photon. Technol. Lett. 14 (5) (2002) 672–674.
[10] S. Trillo, S. Wabnitz, T.A.B. Kennedy, Non linear dynamics of dual-frequency-pumped multiwave mixing in optical fibers, Phys. Rev. A 50 (2) (1994) 1732–1747.
[11] S. Pitois, J. Fatome, G. Millot, Generation of 160-GHz transform-limited pedestal-free pulse train through multiwave mixing compression of a dual frequency beat signal, Opt. Lett. 27 (19) (2002) 1729–1731.