All-fibered high-quality low duty-cycle 160-GHz femtosecond pulse source

Coraline Fortier, Bertrand Kibler, Julien Fatome, Christophe Finot, Stéphane Pitois, Guy Millot

To cite this version:


HAL Id: hal-00406244
https://hal.archives-ouvertes.fr/hal-00406244
Submitted on 16 Apr 2010

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L’archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d’enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.
Abstract: In this paper, we report the experimental demonstration of an all-optical fiber-based 160-GHz femtosecond pulse source exhibiting a duty cycle as low as 1/17. The 380-fs well-separated Gaussian pulses are generated thanks to the strong temporal compression of an initial beat-signal propagating into three distinct segments of optical fiber. Experimental results are supported by numerical simulations based on the generalized nonlinear Schrödinger equation.

All-Fibered High-Quality Low Duty-Cycle 160-GHz Femtosecond Pulse Source


Institut Carnot de Bourgogne, UMR-CNRS 5209 Université of Bourgogne, 9 Avenue Alain Savary, 21078 Dijon, France

Received: 2008, Revised: 2008, Accepted: 2008

Key words: Nonlinear optics in fibers, femtosecond, low duty cycle, pulse compression

PACS: G1.10.Nz, 61.66.Bi

1. Introduction

Laser sources emitting optical pulses at repetition rates ranging from GigaHertz to TeraHertz around 1.5 μm have stimulated a growing interest these last few years since they are involved in a host of applications such as optical sampling, component testing or ultra high capacity transmission system. A well-known and powerful technique used to generate such light sources relies on the temporal compression of a sinusoidal beating propagating in optical fiber line. Indeed, for more than ten years, this method has been successfully applied to generate femto- or picosecond pulse trains using various arrangements of optical fibers [1–15], such as modulational instability [1], dispersion decreasing fibers [2], step-like or comb-like fiber profiles [3–6]. Based on these previous results, Inoue et. al [3] have recently developed a 40-steps pulse generation comb-like setup that enables to transform an initial 160-GHz beat-signal into a train of 320-fs well-separated pulses. In this work, we present an alternative approach to design a very low duty-cycle laser source emitting femtosecond pulses at a repetition rate of 160 GHz. The main advantage of our technique, previously demonstrated at 20- and 40-GHz [7,8], is that it allows to reduce the number of fiber sections to only three stages and reach a much higher output average power.

The first part of this paper is devoted to the presentation of the pulse source through numerical simulations based on the generalized nonlinear Schrödinger equation. Physical comprehension of the compression effect is obtained by showing evolution of the temporal and spectral pulse profiles all along the fiber line. Experimental results, showing the compression of the initial sinusoidal beating into a train of 380-fs pulses, are reported in the second part of the manuscript.

2. Design and Numerical Simulations

First, we study the nonlinear propagation of the initial 160-GHz beat-signal generated by combining two linearly polarized continuous waves with different frequencies and equal powers. Our model is based on the generalized nonlinear Schrödinger equation, including fiber loss and higher-order effects such as third-order dispersion, self-

* Corresponding author: e-mail: julien.fatome@u-bourgogne.fr
dispersion-flattened highly nonlinear fiber (NDF-HNLF)

shaping of the input sinusoidal signal accompanied by its
to be $Z_1$ for achievement of maximum compression with minimum

At the central wavelength of the initial beat signal, i.e.,
signal evolving into compressed pulse train with
pressed pulses.

stage of the setup providing transformed-limited recom-

of anomalous dispersion fiber, which constitutes the final
second segment, the linear chirp of these pulses can there-
pressing into a well-separated Gaussian-like pulse train with

The choice of the second segment is a normal
duty-cycle of 1/5 through the multiple four-wave mixing

parameters are those of the fibers used in our experiments.

The evolution of both intensity and chirp profiles for
one period of the pulse train at different stages is shown
in Fig.2(a,b). We confirm the conversion of the initial si-
nusoidal beating into Gaussian-like pulses with 1.22-ps
FWHM duration (crosses), through the multiple four-wave
mixing process. Fig.2(c) shows the corresponding optical
spectrum fitted by a continuous Gaussian envelope with a
FWHM bandwidth of 0.37 THz, giving a timebandwidth
product of 0.45, very close to the value of 0.441 corre-
responding to transformed-limited Gaussian pulses. Figure
2(a) confirms that the chirp across the pulses is nearly zero.
Next, the second stage provides some linearly chirped
pulses with ~4.3-ps FWHM duration (circles). In partic-
ular, we can note the emergence of some modulated pulse
wings due to the beginning of the overlapping of consec-
utive pulses. This effect suggests that we have reached the
optimum length of the second stage. Finally, the subse-
quent linear compression in the third stage leads to 370-fs
Gaussian-like pulses (solid line) with an excellent symme-
try. Although some residual energy below 5% remains in
low amplitude substructure in the wings, we here obtain
lower pedestals than using soliton effect compression [9].
The combination of segments 2 and 3 has then enabled a
3.5 compression factor of the incoming Gaussian pulses.

Figure 3 shows the 160-GHz sinusoidal input
signal evolving into compressed pulse train with ~370-
fs FWHM pulses in both temporal and spectral domains.

At the central wavelength of the initial beat signal, i.e.,
$\lambda_0 \sim 1555.82$ nm, the NZ-DSF is assumed to have 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. The optimum fiber length
for achievement of maximum compression with minimum
chip and pedestal in the first compressor stage was found
to be $Z_1 \approx 2375$ m. We observe in Fig.1 the temporal re-
shaping of the input sinusoidal signal accompanied by its
spectral broadening through multiple four-wave mixing.

The choice of the second segment is a normal
dispersion-flattened highly nonlinear fiber (NDF-HNLF)
exhibiting losses of 1 dB/km, an anomalous dispersion
of -0.56 ps/nm/km, a nonlinear coefficient of 9 W$^{-1}$.km$^{-1}$,
and a third-order dispersion of 0.01 ps/nm$^2$/km. During
the propagation in this segment, the pulses experience both
temporal and spectral broadenings as well as a significant
reshaping, with a flattening of the central part of the pulse
[11]. A special attention was devoted to prevent tempora-
lar overlapping of consecutive pulses (due to the tempo-
ral broadening) which could lead to detrimental nonlinear
interactions [12]. The optimum fiber length of the second
stage is then $Z_2 = 494$ m. The high nonlinearity of this type
of fiber permits to achieve a strong spectral broadening as
shown in Fig.1. Let us outline that the reduced third-order
compression is crucial to maintain a symmetric broadening.

The final stage is based on a 17-m long SMF-28
segment, assumed to have 0.22 dB/km loss, an anom-
alous dispersion of 17 ps/nm/km, a nonlinear coefficient
of 1.3 W$^{-1}$.km$^{-1}$, and a third-order dispersion of 0.055
ps/nm$^2$/km. As shown in Fig.1, the spectrum bandwidth
remains constant, we then ensure a linear pulse recompre-
sion free from soliton effect compression [12]. All these
parameters are those of the fibers used in our experiments.

The evolution of both intensity and chirp profiles for
one period of the pulse train at different stages is shown
in Fig.2(a,b). We confirm the conversion of the initial si-
nusoidal beating into Gaussian-like pulses with 1.22-ps
FWHM duration (crosses), through the multiple four-wave
mixing process. Fig.2(c) shows the corresponding optical
spectrum fitted by a continuous Gaussian envelope with a
FWHM bandwidth of 0.37 THz, giving a timebandwidth
product of 0.45, very close to the value of 0.441 corre-
responding to transformed-limited Gaussian pulses. Figure
2(a) confirms that the chirp across the pulses is nearly zero.
Next, the second stage provides some linearly chirped
pulses with ~4.3-ps FWHM duration (circles). In partic-
ular, we can note the emergence of some modulated pulse
wings due to the beginning of the overlapping of consec-
utive pulses. This effect suggests that we have reached the
optimum length of the second stage. Finally, the subse-
quent linear compression in the third stage leads to 370-fs
Gaussian-like pulses (solid line) with an excellent symme-
try. Although some residual energy below 5% remains in
low amplitude substructure in the wings, we here obtain
lower pedestals than using soliton effect compression [9].
The combination of segments 2 and 3 has then enabled a
3.5 compression factor of the incoming Gaussian pulses.

Figure 2(d) shows the Gaussian-like optical spectrum of the
compressed pulses at the third stage output with ~1.2-THz
FWHM bandwidth.

3. Experimental Results

A schematic of the experimental setup is shown in Fig-
ure 3. The initial beat-signal is generated by the superpo-
sition of two continuous waves delivered by two linearly-
polarized external-cavity lasers (ECL) separated by 160
GHz around 1555 nm and combined by means of a 50:50

(c) 2008 by ASTRO, Ltd.
Published exclusively by WILEY-VCH Verlag GmbH & Co. KGaA
Numerical simulations results: Evolution of the chirp (a) and intensity (b) profiles at different stages of the setup (dashed line: compressor input, crosses: first stage output, circles: second stage output, solid line: compressor output). Optical spectra and their corresponding gaussian fit (dashed line) at both the first stage output (c) and the end of the pulse compressor (d).

Experimental setup

A 100-MHz phase modulation is then applied to enlarge the diode linewidth so as to work far below the Brillouin scattering threshold. The beat-signal is finally amplified at an average power of 27 dBm by means of a polarization-maintaining Erbium-doped fiber amplifier (EDFA) and injected into the first compression stage.

This first stage converts the initial beat-signal into a 1.3-ps Gaussian pulse train through a multiple four-wave mixing process taking place into a 1-km long NZ-DSF having an anomalous dispersion of D=1 ps/km.nm [10]. The second stage, which involves 500 m of commercially-available HNLF from OFS (parameters given in section 2), provides the passive reshaping of the Gaussian pulses into linearly chirped pulses, thanks to the combined effects of self-phase modulation and normal dispersion [13]. The final temporal compression is performed in the third stage: 17 m of SMF allows the compensation of the linear chirp and thus the generation of ultrashort quasi-gaussian pulses. At the output of the fiber line, the resulting pulses were analyzed by means of an SHG-based autocorrelator, an optical spectrum analyzer (OSA) and a home-made frequency-resolved optical gating (FROG) setup [15]. We can notice π-jump phase between two consecutive pulses which originates from the initial beat-signal.

We have represented in 4 the experimental autocorrelation results at each step of the fiber compressor line. Crosses in Fig. 4a represents the 1.3-ps Gaussian pulses generated at the first fiber output thanks to the nonlinear compression of the initial sinusoidal beating. The corresponding spectrum, visible in Fig. 4b, reveals the large number of sidebands generated by the four-wave mixing process which takes place in this NZ-DSF [14].

The spectrum at the output of the HNLF (second stage) is shown in Fig. 4c. As can be seen circles in Fig. 4a, the transformation of the Gaussian pulses into linearly chirped pulses in the normally dispersive fiber is accompanied by a large broadening of the intensity spectrum.

Finally, solid line in Fig. 4a represents the autocorrelation profile at the fiber line output, after the quasi-linear temporal compression which occurs in the last piece of fiber (SMF). Assuming Fourier transformed-limited pulses, one may infer a FWHM temporal width equal to 380-fs. We have also observed that the spectra after the second- and third-stage outputs are nearly the same. This result is not surprising since light propagation in the last stage is essentially dominated by dispersive (linear) effects. Moreover, we have found that this output spectrum can be accurately fitted by a Gaussian envelope (dashed line in Fig. 4c) having a full-width at half-maximum of 1.1 THz. The Time-Bandwidth product of 0.45 is fully consistent with the value 0.44 usually associated with Fourier limit Gaussian pulses.
Figure 5  a) Intensity and phase profile of 160-GHz pulse train at stage 3 obtained by FROG measurement.

This last result was confirmed by the FROG measurements represented in Fig. 5. The retrieved intensity profile (solid line) confirms that the 160-GHz pulses have a Gaussian shape with a FWHM of 380 fs. Given the period of 6.25 ps, this constitutes a very low duty cycle of 1/17. The retrieved phase (dashed line) is also pretty flat, confirming that pulses are nearly transform-limited. Finally, the available peak power exceeds 6 W, which is quite high compared to ref. [3], essentially because of a large reduction of the number of fiber sections spliced together. This then leads to an output average power as high as 400 mW which is beneficial in the context of optical nonlinear processing. We obtained high peak-to-pedestal ratio of more than 18dB.

4. Conclusion

In conclusion, we have generated and characterized a 160-GHz Gaussian pulse source having a FWHM of 380 fs corresponding to a very low duty-cycle of 1/17. The experimental setup is based on the temporal compression of an initial beat-signal into only three stages of optical fiber, validating this alternative method to comb-like dispersion decreasing techniques. We finally believe that this kind of sources could find many applications in the field of ultrafast optics such as optical sampling or ultrahigh capacity transmission.

Acknowledgment

We would like to acknowledge financial support of the Agence National de la Recherche (Projet ILLADE).

References