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Published in:
Optics Express

Link to article, DOI:
10.1364/OE.21.026044

Publication date:
2013

Document Version
Publisher's PDF, also known as Version of record

Dynamic characterization and amplification of sub-picosecond pulses in fiber optical parametric chirped pulse amplifiers

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Abstract: We show a first-time demonstration of amplification of 400 fs pulses in a fiber optical parametric amplifier. The 400 fs signal is stretched in time, amplified by 26 dB and compressed back to 500 fs. A significant broadening of the pulses is experimentally shown due to dispersion and limited gain bandwidth both in saturated and unsaturated gain regimes.

OCIS codes: (060.2320) Fiber optics amplifiers and oscillators; (190.4970) Parametric oscillators and amplifiers.

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1. Introduction

Optical amplification of signals reaching multi-terabit per second per channel is becoming increasingly relevant following the recent demonstrations of single wavelength channel systems at bit rates of 1.28 Tbit/s, 5.1 Tbit/s or even 10.2 Tbit/s [1–3], all using ultra-short pulses with pulse widths on the order of 500 fs. Therefore, a broadband amplification scheme is required for such wide bandwidth signals. Fiber optical parametric amplifiers (FOPAs) relying on highly nonlinear fibers (HNLFs) are promising candidates thanks to their inherent compatibility with fiber optic systems and their ability to provide gain over a broad bandwidth, limited only by fulfillment of the phase matching condition [4].

Fiber optical parametric chirped pulse amplification (FOPCPA) has been proposed and investigated numerically in the femtosecond regime in [5], followed by a number of demonstrations for picosecond [6, 7] and sub-picosecond pulses down to 750 fs [8]. However, the amplification of pulses of duration compatible with Tbaud transmission (i.e. less than 500 fs) has never been demonstrated so far.

In this work, we investigate experimentally the effect of parametric amplification on 400 fs pulses, focusing on the distortion of the amplified pulses for different amplification levels both in the saturated and unsaturated gain regimes. Significant pulse distortion due to dispersion and limited FOPA gain bandwidth is reported. Based on these results, we set the best FOPA configuration to demonstrate, for the first time to our knowledge, the amplification of Tbaud-class pulses in a fiber optical parametric amplifier. After time stretching, the 400 fs pulses are first amplified by 26 dB and then compressed back to 500 fs, showing the compatibility of FOPAs with ultra-high speed pulse amplification.

2. Dynamic characterization of the FOPCPA

In this section the amplification effects on the full-width at half maximum (FWHM) of the pulses and the pulse shape are reported.

2.1. Experimental setup

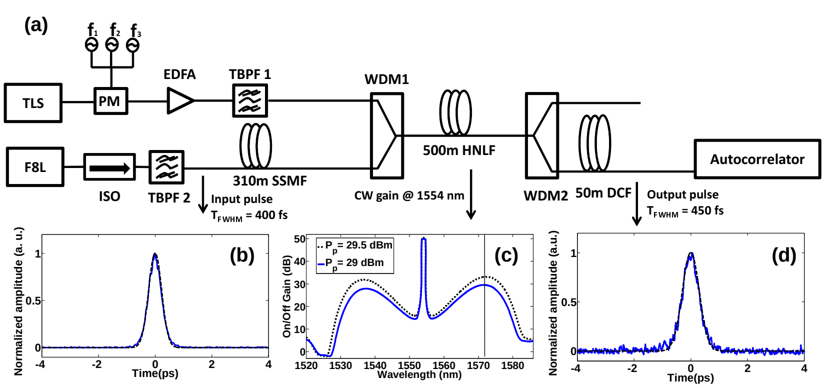

Fig. 1. (a) Experimental setup of the FOPCPA for the pulses dynamic characterization. (b) Autocorrelation trace of the 400 fs input pulse. (c) CW FOPA gain for two different pump levels (the vertical line indicates the signal central wavelength). (d) compressed output pulse autocorrelation measured with the pump signal switched off.

The experimental setup is shown in Fig. 1(a). A continuous wave (CW) tunable laser source (TLS) is used as pump source ($\lambda_p = 1554$ nm) and the emitted light is subsequently phase modulated using three combined radio-frequencies (RFs) to broaden the pump spectrum in order to increase the stimulated Brillouin scattering (SBS) threshold. The modulation frequencies for SBS suppression ($f_1 = 66$ MHz, $f_2 = 550$ MHz and $f_3 = 865$ MHz) are optimized

#193219 - $15.00 USD Received 1 Jul 2013; revised 10 Oct 2013; accepted 16 Oct 2013; published 24 Oct 2013

by minimizing the reflected pump power. The pump is then amplified in an erbium-doped fiber amplifier (EDFA) and a tunable optical bandpass filter (TBPF1) with a 0.8 nm FWHM bandwidth is used to suppress the out-of-band amplified spontaneous emission (ASE) noise introduced by the EDFA. The pump wavelength is chosen only a few nanometers above the HNLF zero-dispersion wavelength (1550.4 nm) in order to have a gain as uniform as possible over a broad bandwidth. On/off CW-gains (i.e. the gain spectra obtained by using a CW source to generate the input signal) of the FOPA under investigation are shown in Fig. 1(c) for two pump input power levels. The vertical line indicates the signal central wavelength used for pulse amplification. It is worth to notice that the signal is centered with respect to one of the lobes in the FOPA gain spectrum for a pump input power of 29 dBm, providing a CW on/off gain of 28 dB.

The signal is generated by a mode-locked figure-of-eight laser (F8L) [9], filtered with a 9 nm broadband filter (TBPF2) to generate Gaussian pulses at 1571.6 nm with a FWHM of 400 fs and a 28 MHz repetition rate. The autocorrelation trace of the obtained pulses is shown in Fig. 1(b). The time-bandwidth product (TBP) of the generated pulses is 0.443, corresponding to that of Gaussian transform-limited pulses. An isolator (ISO) is placed at the output of the F8L to prevent back reflected light from affecting the mode-locking. The signal pulses are stretched to approximately 53 ps in 310 m of standard single mode fiber (SSMF) in order to avoid saturation of the FOPA or supercontinuum generation in the HNLF [9]. They are then combined with the pump via a wavelength division multiplexer (WDM1) into a 500 m long HNLF, with a non-linear coefficient of 10.7 $W^{-1} \cdot km^{-1}$ and dispersion slope of 0.018 $ps/(nm^2 \cdot km)$. The signal at the output of the HNLF is filtered by WDM2 and then compressed with a 50 m long dispersion compensating fiber (DCF), with a total dispersion of 5.89 ps/nm at 1550 nm. To characterize the broadening of the pulses due only to the amplification, the length of DCF is adjusted to achieve the minimum signal pulse width at its output when the pump is turned off. Figure 1(d) shows the corresponding autocorrelation trace.

2.2. Results

A characterization of the full-width at half maximum (T_{FWHM}) of the pulses in unsaturated and saturated regimes, i.e. at signal input average power levels of -27 dBm and -7 dBm, respectively, has been performed as a function of the pump input power to the HNLF. The results are shown in Fig. 2(a) along with the corresponding on/off gain measurements in Fig. 2(b). Figure 2(a) shows that T_{FWHM} increases with increasing pump power, i.e. increasing gain, both in the saturated and the unsaturated regimes. When the pump power is off, the output pulsewidth is approximately 450 fs but, as the pump is turned on and the input pulsed signal is amplified, the pulsewidth broadens. In particular, considering the optimal pump power for which the signal is centered with respect to one of the lobes in the FOPA gain spectrum ($P_p = 29$ dBm), T_{FWHM} is 700 fs and 570 fs for signal input average power levels of -27 dBm and -7 dBm, corresponding to 26 dB and 7.5 dB of amplification, respectively. The pulse broadening needs to be compensated for the short pulses amplification experiment. The insets show autocorrelation traces fitted with Gaussian pulse shape curves. When the FOPCPA is saturated, a higher energy with respect to the unsaturated regime is observed in the leading and trailing edges of the pulse. This reshaping of the pulses causes discrepancies with the Gaussian fit. For -7 dBm of signal input average power, T_{FWHM} is reduced by approximately 20% compared to a signal input average power of -27 dBm, considering the same pump input power. The reduction of the FWHM of the pulses due to saturation in FOPCPAs has already been shown in [6], where 6.4 ps pulses were used to characterize the effect of saturation in FOPCPAs, but no signs of pulse reshaping were reported. This may be explained by the lower dispersion effects experi-

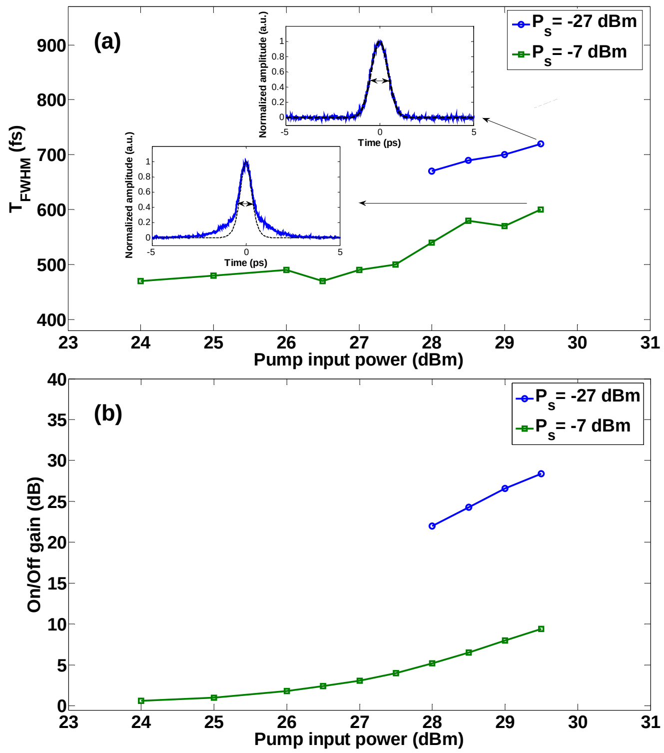

Fig. 2. (a) Pulsewidth of the amplified signal as a function of pump power at the input of the HNLF in the saturated ($P_s = -7$ dBm) and unsaturated ($P_s = -27$ dBm) regimes. The insets show selected autocorrelation traces. (b) Corresponding measured on/off gain.

enced by the 6.4 ps pulses with respect to the 400 fs pulses employed in this experiment. We attribute the increased energy on the leading and trailing edges of the pulses to the interplay between SPM and high order dispersion in the FOPCPA, reshaping the pulses and, thereby decreasing T_{FWHM}. The gain spectrum profile of the FOPA also plays a key role in the narrowing and reshaping of the pulses in the time domain. To understand this effect, optical spectra at the output of the HNLF are considered in Fig. 3. The optical spectra are measured with the pump power switched on (29 dBm) and off for $P_s = -27$ dBm and $P_s = -7$ dBm. The steep edges in the signal spectra with the pump turned off are due to WDM1, which couples the signal with the pump (the wavelength dividing the pass band and the reflection band is approximately 1559 nm). A broadening of the signal spectrum is visible when the amplifier operates in the saturated regime compared to the unsaturated regime, validating a narrowing of the pulsewidth in the time domain. In particular, a broadening of the FWHM spectrum from 9 nm to approximately 14 nm is observed in the spectra for a signal input average power of -7 dBm. In the unsaturated regime (i.e. $P_s = -27$ dBm), the FWHM of the spectrum remains unchanged at 9 nm. The narrowing and reshaping of the pulses in the saturation regime is better observed in Fig. 4 (a) and (b), where the pulsewidth of the amplified signal is shown as a function of the signal input average power together with the corresponding on/off gain. It is noted that T_{FWHM} decreases as the signal power is increased, while pulse reshaping appears as saturation is gradually reached. In fact, discrepancies with the Gaussian fit increase with increasing signal input average power, as can be noticed from the insets in Fig. 4(a). For a signal input average power

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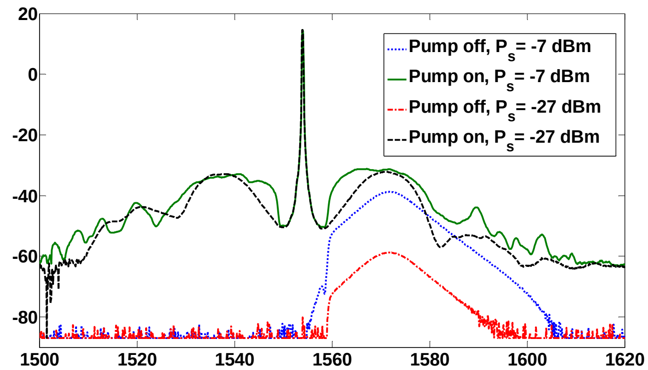

Fig. 3. Optical spectra measured at the output of the HNLF with the pump switched off and on ($P_p = 29$ dBm) for $P_s = -27$ dBm and $P_s = -7$ dBm.

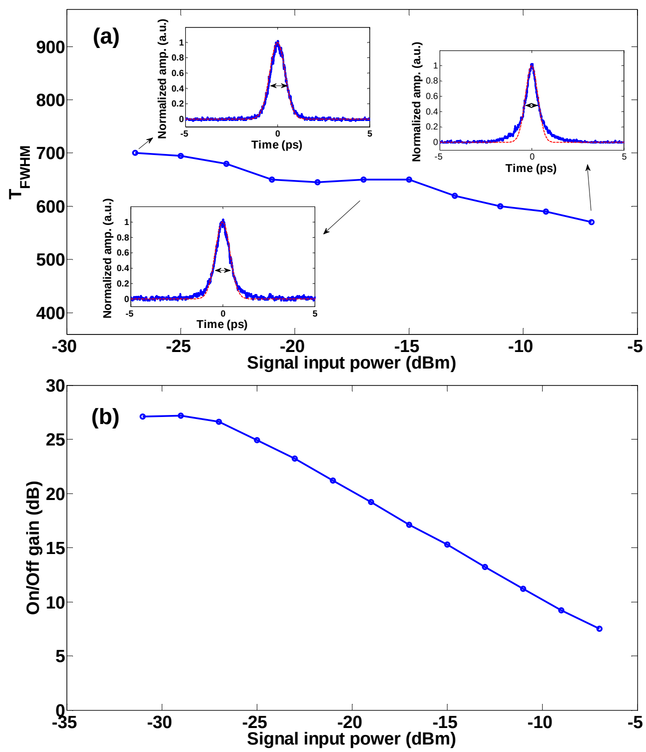

Fig. 4. (a) Pulsewidths of the amplified signal as a function of the signal input average power with a pump power of 29 dBm. The insets show selected autocorrelation traces. (b) Corresponding measured on/off gain.

of -27 dBm no reshaping of the pulse is observed. This, together with the fact that the FWHM of the spectrum remain unchanged for $P_s = -27$ dBm, makes the unsaturated regime more suitable for the amplification experiment of very short pulses. Therefore, the amplification scheme of the 400 fs pulses is set by choosing a signal input power of -27 dBm and a pump input power of 29 dBm. This experiment is described in the next section.

3. Amplification of 400 fs pulses in the FOPCPA

In this section, the experimental demonstration of fiber optical parametric amplification of 400 fs pulses in the unsaturated regime is reported. The experimental setup is shown in Fig. 5. The differences, with respect to the setup shown in Fig. 1, are the use of a 10 dB coupler and

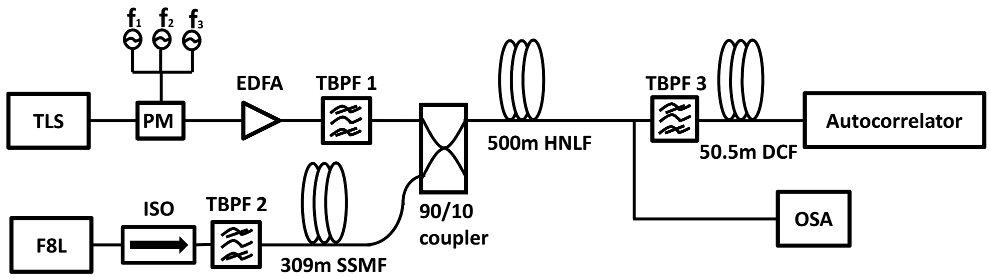

Fig. 5. Experimental setup of the FOPCPA for the amplification of the 400 fs pulses with a pump input power of 29 dBm and signal input average power of -27 dBm.

a filtering stage made by a cascade of three broadband filters (TBPF3) instead of WDM1 and WDM2, respectively. The choice of the filtering stage instead of the WDM2 at the output of the HNLF was made to remove an asymmetry in the pulses spectrum, which could induce distortion in the pulses. The filtering stage response is shown in Fig. 6, where the signal spectra at the input and at the output of the the cascade of filters are illustrated with the pump turned off. The FWHM of the filtering stage is approximately 16 nm. The stretching/compression stages

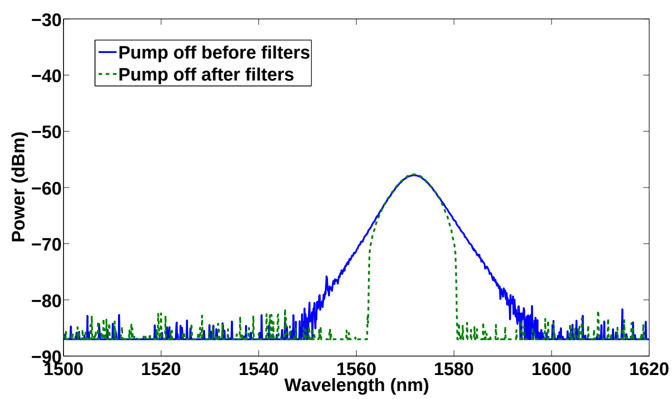

Fig. 6. Optical signal spectra measured at the output of the HNLF (solid line) and at the output of the filtering stage (dash-dot line) with the pump switched off.

are also different in the setup in Fig. 5 with respect to the setup in Fig. 1, since the compression is now optimized when the signal is amplified and the amplification adds chirp to the pulses, as described in Sec. 2.2. The pump wavelength is set at 1554 nm and the pump power is 29 dBm, resulting in an on/off CW-gain of 28 dB. The 400 fs signal is stretched by 309 m of SSMF, amplified by 26 dB and then compressed back to 500 fs by a 50.5 m long DCF. The spectrum of the pulsed signal at the output of the HNLF is shown in Fig. 7 when the pump is either switched off or on. The on/off gain at the signal wavelength is 26 dB, i.e. 2 dB lower compared to the

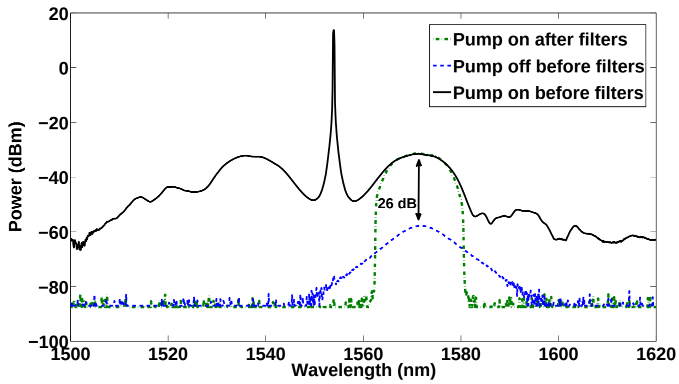

Fig. 7. Optical spectra measured at the output of the HNLF with the pump switched off (dashed blue line) and on (solid black line) with a pump power of 29 dBm.

CW gain. This is due to the fact that the amplifier is working close to the saturated regime. It is necessary to find a compromise between the stretching factor and the saturation of the amplifier. A too low stretching factor, i.e. a too high peak power, saturates the amplifier, while a too high stretching factor makes the dispersion management to compress back the pulse after amplification challenging. The filtered amplified signal is also shown in Fig. 7. The peak power of the signal after the filtering stage and the compression is measured to be around 9.3 W for a pulsewidth of 500 fs. The autocorrelation traces measured before the stretching SSMF and after the amplification, filtering and compression in the DCF are shown in Fig. 8 (a) and (b), respectively. The noise on the output trace is due to the high losses in the filtering stage. The measured data was fitted to a Gaussian curve. The compressed pulse is broader with respect to the input pulse by approximately 100 fs. This is believed to be due to two main factors. First, the lack of compensation of high-order dispersion terms adds some chirp to the pulse. In fact, the pulses were stretched by more than two orders of magnitude in the SSMF and even in the dynamic characterization experiment discussed in Sec. 2, it was not possible to completely compress the pulses back to 400 fs, but only down to 450 fs. Since other effects, apart from the dispersion, were not acting on the pulses when the pump was switched off, the difference between the pulses at the input of the stretcher and at the output of the compressor can only be explained by the lack of compensation of higher-order dispersion terms. Secondly, a significant pulse broadening was observed possibly due to the limited gain bandwidth of the FOPA, introducing a frequency filtering effect. This broadening was only partially compensated at the output of the DCF. Furthermore, the filtering stage also contributes to the broadening of the pulse in time due to the reduction of the frequency bandwidth of the filtered signal, affecting the measurements. However, this contribution has been measured to be small and almost completely compensated in the DCF.

One should note that that the present study of the dynamics of the pulse is performed at a low repetition rate of 28 MHz. At higher repetition rates, the dispersed pulses will overlap and may therefore interact via the nonlinearity of the HNLF. This may result in intra-channel nonlinear effects [10] that will degrade the amplified waveform following compression. A full analysis of this effect is however beyond the scope of this paper and is left for future work.

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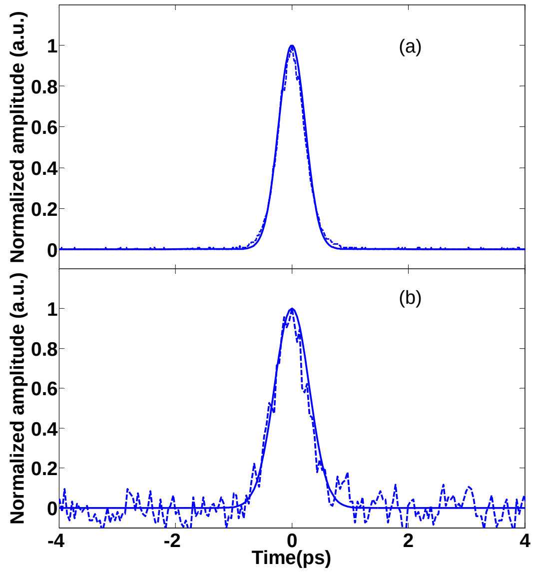

Fig. 8. Autocorrelation traces of the signal (a) at the input of the SSMF, corresponding to a pulsewidth of 400 fs and (b) at the output of the DCF, corresponding to a pulsewidth of 500 fs.

4. Conclusion

Amplification of short nearly transform-limited pulses of 9 nm bandwidth and 400 fs pulse duration was demonstrated, for the first time to our knowledge, in a fiber optical parametric chirped pulse amplification configuration. A dynamic characterization of the FOPCPA was performed both in the saturated and the unsaturated regimes. It was shown that the FWHM of the pulses is increased with increasing gain in the FOPCPA. Furthermore, the pulsewidth compressed as saturation was reached. A broadening of the spectrum was observed, showing that a chirp has been added to the pulse as the amplifier was saturated. However, in saturation, a higher energy with respect to the unsaturated regime is observed in the leading and trailing edges of the pulses, reshaping them and rendering the saturated amplifier unsuitable for undistorted amplification. After the optimization of the parameters of the amplifier, 400 fs pulses were first stretched to 50 ps, amplified by 26 dB in a fiber optical parametric amplifier and then compressed back to 500 fs. This demonstration opens the way to parametric amplification of Tbaud single wavelength channel signals [1–3].

Acknowledgments

OFS Fitel Denmark is acknowledged for providing the HNLFs. The Danish Research Council for Technology and Production Sciences is acknowledged for financial support (project 09-066562).