Parametric amplification and compression to ultrashort pulse duration of resonant linear waves

C. Aguergaray[1], T. V. Andersen[2], D. N. Schimpf, O. Schmidt, J. Rothhardt, T. Schreiber, J. Limpert

Friedrich Schiller University Jena, Institute of Applied Physics, Albert-Einstein-Str. 15, 07745 Jena, Germany
1 also with CELIA, Université Bordeaux 1, 351 cours de la Libération, F-33405 Talence, France
2 also with NKT Research, Blokken 84, DK-3460 Birkerød, Denmark
Claude.Aguergaray@celia.u-bordeaux1.fr Jens.Limpert@uni-jena.de

E. Cormier

CELIA, Université Bordeaux 1, 351 cours de la Libération, F-33405 Talence, France

A. Tünnermann

Fraunhofer Institute for Applied Optics and Precision Engineering, Albert-Einstein-Str. 7, 07745 Jena, Germany
and
Friedrich-Schiller-University Jena, Institute of Applied Physics, Albert-Einstein-Str. 15, D-07745 Jena, Germany

Abstract: We report on an optical parametric amplification system which is pumped and seeded by fiber generated laser radiation. Due to its low broadening threshold, high spatial beam quality and high stability, the fiber based broad bandwidth signal generation is a promising alternative to white light generation in bulky glass or sapphire plates. We demonstrate a novel and successful signal engineering implemented in a setup for parametric amplification and subsequent recompression of resonant linear waves resulting from soliton fission in a highly nonlinear photonic crystal fiber. The applied pump source is a high repetition rate ytterbium-doped fiber chirped pulse amplification system. The presented approach results in the generation of ~50 fs pulses at MHz repetition rate. The potential of generating even shorter pulse duration and higher pulse energies will be discussed.

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References and links

1. V. Bagnoud, F. Salin, "Amplifying laser pulses to the terawatt level at a 1-kilohertz repetition rate," Appl. Phys. B **70** [Suppl.], S165–S170 (2000).
2. I.N. Ross , P. Matousek, M. Towrie, A.J. Langley. J.L. Collier, "The prospects for ultrashort pulse duration and ultrahigh intensity using optical parametric chirped pulse amplifiers," Opt. Commun. **144**, 125-133 (1997).
3. G. Cerullo and S. Silvestri, "Ultrafast optical parametric amplifiers," Rev. Sci. Instrum. **74**, 1 (2003).
4. V.V. Lozhkarev, G.I. Freidman, V.N. Ginzburg, E.V. Katin, E.A. Khazanov, A.V. Kirsanov, G.A. Luchinin, A.N. Malshakov, M.A. Martyanov, O.V. Palashov, A.K. Poteomkin, A.M. Sergeev, A.A. Shaykin and I.V. Yakovlev, S.G. Garanin, S.A. Sukharev, N.N. Rukavishnikov, A.V. Charukhchev, R.R. Gerke, V.E. Yashin, "200 TW 45 fs laser based on optical parametric chirped pulse amplification," Opt. Express **14**, 1, 446 (2006).
5. A. Killi, A. Steinmann, G. Palmer, U. Morgner, H. Bartelt, and J. Kobelke, "Megahertz optical parametric amplifier pumped by a femtosecond oscillator," Opt. Lett. **31**, 125-127 (2006).
6. F. Tauser, F. Adler, and A. Leitenstorfer, "Widely tunable sub-30-fs pulses from a compact erbium-doped fiber source," Opt. Lett. **29**, 5, 516 (2004)

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7. C. Y. Teisset, N. Ishii, T. Fuji, T. Metzger, S. Köhler, R. Holzwarth, A. Baltuška, A. M. Zheltikov, and F. Krausz, "Soliton-based pump–seed synchronization for few-cycle OPCPA," Opt. Express, **13**, 17, 6550 (2005).
8. J. Limpert, C. Aguergaray, S. Montant, I. Manek-Hönninger, E. Cormier, F. Salin, "Ultra-broad bandwidth parametric amplification at degeneracy," Opt. Express **13**, 19, 7386 (2005).
9. T. V. Andersen, O. Schmidt, C. Bruchmann,, J. Limpert, C. Aguergaray, E. Cormier and A. Tünnermann, "High repetition rate tunable femtosecond pulses and broadband amplification from fiber laser pumped parametric amplifier," Opt. Express **14**, 4765 (2006).
10. R. Butkus, R. Danielius, A. Dubietis, A. Piskarskas, A. Stabinis, "Progress in chirped pulse optical parametric amplifiers," Appl. Phys. B **79**, 693–700 (2004).
11. www.sandia.gov/imrl/X1118/xxtal.htm.
12. T. Wilhelm, J. Piel, and E. Riedle, "Sub-20-fs pulses tunable across the visible from a blue-pumped single-pass noncollinear parametric converter," Opt. Lett. 22, 19, 1494 (1997).
13. Niels Asger Mortensen, "Effective area of photonic crystal fibers," Opt. Express **10**, 7, 341 (2002),
14. J. M. Dudley, G. Genty, and S. Coen, "Supercontinuum generation in photonic crystal fiber," Rev. Mod. Phys. **78**, 1135 (2006).
15. Kodama, Y., and A. Hasegawa, , "Nonlinear pulse propagation in a monomode dielectric guide," IEEE Photonics Technol. Lett. QE-**23**, 510–524, 1987.
16. G.P. Agrawal, in : Nonlinear Fiber Optics, Academic Press, San Diego, NY, 1995.
17. Akhmediev, N., and M. Karlsson, "Cherenkov radiation emitted by solitons in optical fibers," Phys. Rev. A **51**, 2602–2607, 1995
18. T. Schreiber, T. Andersen, D. Schimpf, J. Limpert, and A. Tünnermann, "Supercontinuum generation by femtosecond single and dual wavelength pumping in photonic crystal fibers with two zero dispersion wavelengths," Opt. Express **13**, 23, 9556-9569 (2005).
19. A.V. Husakou and J. Herrmann, "Supercontinuum Generation of Higher-Order Solitons by Fission in Photonic Crystal Fibers," Phys. Rev. Lett. **87**, 20, 203901 (2001).
20. J. Dudley and S. Coen, "Fundamental limits to few-cycle pulse generation from compression of supercontinuum spectra generated in photonic crystal fiber," Opt. Express **12**, 2423-2428 (2004).
21. J. Limpert, F. Röser, T. Schreiber, and A. Tünnermann, "High-power ultrafast fiber laser systems," IEEE J. Sel. Top. Quantum Electron. **12**, 2, 233-244 (2006).
22. J. Limpert, A. Liem, M. Reich, T. Schreiber, S. Nolte, H. Zellmer, A. Tünnermann, J. Broeng, A. Petersson, and C. Jakobsen, "Low-nonlinearity single-transverse-mode ytterbium-doped photonic crystal fiber amplifier," Opt. Express **12**, 7, 1313–1319 (2004).
23. G. Cerullo, M. Nisoli, S. Stagira, and S. D. Silvestri, "Sub 8-fs pulses from an ultra broadband optical parametric amplifier in the visible," Opt. Lett. **23**, 1283–1285 (1998).
24. I. N. Ross, P. Matousek, G. H. C. New, and K. Osvay, "Analysis and optimization of optical parametric chirped pulse amplification," J. Opt. Soc. Am. B **19**, 2945–2956 (2002).
25. F. Tauser, A. Zach, F. Lison, F. Adler, K. Moutzouris, and A. Leitenstorfer, "Two Alternative Approaches to Broadband Visible Light Generation with Mode-Locked Erbium Fiber Lasers," in *Conference on Lasers and Electro-Optics/Quantum Electronics and Laser Science Conference and Photonic Applications Systems Technologies*, Technical Digest (CD) (Optical Society of America, 2006), paper JWB37. http://www.opticsinfobase.org/abstract.cfm?URI=CLEO-2006-JWB37

1. Introduction

Ultrashort and high peak power optical pulses have become extremely important in sources for numerous applications such as spectroscopy, detection or high field physics. In fact, considerable progress has been made over the last decade to provide high peak power femtosecond sources based on Ti:Sapphire lasers and amplifiers [1]. Such systems have proven to be a very reliable option at low repetition rates. However, the complexity, a limited tunability of ultrashort laser pulses and the limited average power due to thermo-optical problems restrict the application potential of those bulk solid-state laser systems.

The benefits of optical parametric amplification (OPA) to generate high peak power pulses have been clearly demonstrated [2]. The high single-pass gain, the good beam quality and the remarkable contrast ratio of parametric process are very attractive. In addition, the broad gain bandwidth of optical parametric amplifiers in distinguished configurations allows for the generation of intense few-cycle pulses in the UV to the NIR spectral range [3]. Furthermore, due to the optically fulfilled energy conservation during the nonlinear amplification process, parametric amplifiers are immune against thermo-optical problems and therefore very suitable for high average power (i.e. high repetition rate) amplification.

Peak powers approaching the Peta-Watt level have been obtained recently by optical parametric chirped pulse amplification (OPCPA) [4]. This impressive performance suffers

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from a low repetition rate and the scalability in terms of average power, which is restricted by the pump source. Ultra-short and intense laser sources are mainly used in high field physics to probe processes whose probabilities are often very small. For instance, Attoscience uses weak XUV pulses produced with such IR ultra-short pulses. As a consequence, detection of the XUV induced processes requires very sophisticated and sensitive apparatus. An increase of few orders of magnitude in the repetition rate will clearly provide a tool, which allows to break the actual limits and open the way to investigate in-depth phenomena.

Short pulse amplification in OPA systems requires a broadband input signal. The most common approach relies on generating a broadband signal through filamentation in a glass or a sapphire plate [5]. In this case, very short pulses with pulse energies in the µJ range are necessary to create stable filamentation and thus stable gain and amplification in the OPA. To alleviate the absence of such short and intense pulse sources we have chosen to generate a broad signal using highly nonlinear photonic crystal fibers (PCF) [6]. Those fibers just need few nanojoules to deliver very stable supercontinua covering the interesting wavelengths for parametric amplifiers. The potential of this technique, which additionally provides an all optical synchronization of pump and signal has already been demonstrated [7]. Generating the signal in a PCF a broadband amplification, potentially over more than one optical octave [8], or femtosecond pulses tunable from 700 nm to 1500 nm [9], have been reported. Alternatively, starting from a broadband signal generated by a short pulse solid-state oscillator in the 800 nm wavelength range, a well defined part of the pulse energy can be transferred to the wavelength of the pump source around 1060 nm in form of a soliton [7]. Subsequent amplification in regenerative amplifiers and frequency doubling allowed for the parametric amplification of the initial broadband pulses.

In this contribution, we report on a novel technique to provide a broad bandwidth signal overlapping with the amplification range of a non-collinear parametric amplifier (NOPA). The gain bandwidth of a NOPA can extend over more than 200 THz, hence, this configuration is predestinated to generate intense few cycle optical pulses. Starting from near-infrared pulses from the oscillator, the signal for the NOPA is a continuum generated in a photonic crystal fiber. For given input parameters, such a continuum exhibits a very interesting behavior dominated by a single resonant linear wave, which is identified as the precondition for a compressible continuum to ultra-short pulse duration. This particular signal engineering for parametric amplification will be discussed in detail. Its implementation in a NOPA system has allowed the generation of 55 fs pulses at 1 MHz repetition rate, using a short pulse fiber laser as the pump source. To our knowledge, this represents the first demonstration of amplification of resonant linear waves from soliton fission in a power scalable architecture. The potential of this approach to generate significantly shorter pulses is discussed as well.

2. Fiber based generation of broad bandwidth signal

Parametric amplification is receiving much attention due to its potential for generating high peak power pulses. As it uses the instantaneous interaction between spatially and temporally overlapped pump, signal and idler pulses an enormous gain (larger than 10^6) and extreme broad bandwidth (>200 THz) is achievable. In most cases the pump source of such an ultrafast parametric amplifier is the second harmonic of a Ti:Sapphire or Ytterbium doped short pulse laser system [10].

It is well known that in a non-collinear beam geometry the group-velocity mismatch between pump, signal and idler waves can be efficiently compensated, resulting in a very broad phase-matching bandwidth [11,12]. Figure 1 shows the calculated phase matching curve of a type 1 BBO crystal pumped at 515 nm used under a non-collinearity angle (pump tilt) of 2.6°. In this simple configuration a phase-matched bandwidth of about 200 nm, centered around 800 nm, is revealed at a constant internal signal of 22°. Therefore, such a configuration is predestinated to generate intense few-cycle optical pulses.

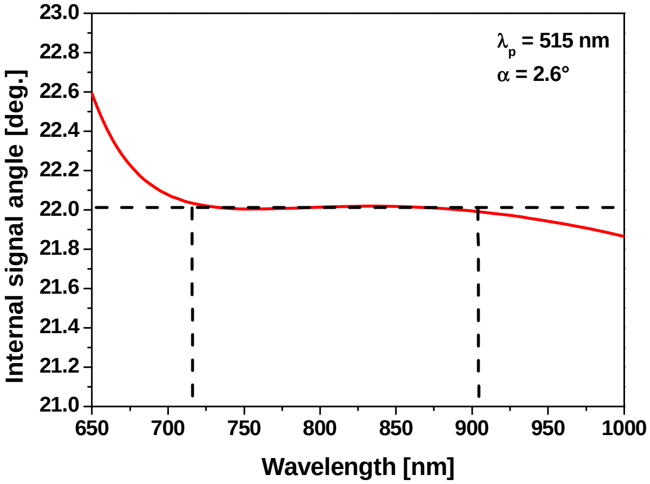

Fig. 1. Calculated phase-matching curve of a Type 1 BBO crystal pumped by 515 nm light at a pump tilt angle of 2.6°.

The most common technique to create a wide spectrum as a signal for an ultrafast optical parametric amplifier is white light generation using filamentation in a glass or sapphire plate. Dominated by self phase modulation this method produces a signal with a simple and well defined spectral phase, leading to a rather easy recompression using conventional techniques. However, this approach requires a considerable amount of peak power (typically several MW) to reach the filamentation threshold. Furthermore, initial ultrashort pulse duration with well defined focusing into the plate is needed to generate stable filamentation while avoiding the creation of multi-filaments.

We propose an alternative approach to generate broad signal whose bandwidth overlaps the gain bandwidth of a non-collinear parametric amplifier. It is based on nonlinear broadening mechanisms in optical fibers, and in particular photonic crystal fibers. The main advantages of this concept are the significantly smaller broadening thresholds (approximately few kW of peak power), the possible longer initial pulse duration and the power independent perfect spatial mode quality, which is given by the fiber design. More specifically, photonic crystal fibers can be designed to be endlessly single-mode, which means single-mode for all wavelengths [13].

The measured part of such a supercontinuum emitted by a photonic crystal fiber is shown in Fig. 2. This spectrum is generated using an 80 cm long PCF with a zero-dispersion wavelength at 975 nm. Few nJ of 400 fs pulses at 1030 nm are launched. As it is revealed the continuum bandwidth optimally fits the phase-matched wavelengths of the above described non-collinear configuration in a BBO crystal.

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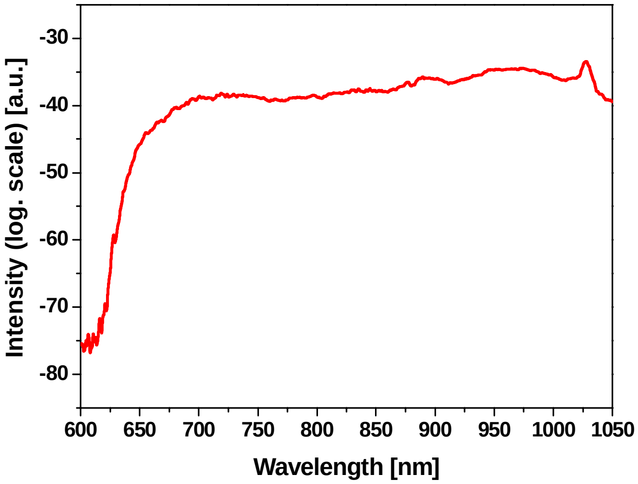

Fig. 2. Typical visible part of a supercontinuum generated in a photonic crystal fiber.

However, such a supercontinuum has its origin in a rather complicated broadening mechanism determined by soliton dynamics for the pulse parameters discussed here [14].

The mechanism should be described briefly: Short optical pulses are launched into the fiber at a wavelength of anomalous dispersion. Depending on the initial peak power P_0, pulse duration T_0 and group-velocity dispersion β_2 at the wavelength of the launched pulses, solitons can be excited. More specifically, if only second order dispersion and self-phase modulation is taken into account, the pulse excites a Nth order soliton, which can be described as a superposition of N fundamental solitons (indexed with k) having different peak powers P_k and durations T_k according to Eq. 1 [15], where γ is the nonlinear coefficient [16] :

$$P_k = \frac{(2N-2k+1)^2}{N^2} \cdot P_0 \qquad T_k = \frac{T_0}{2N-2k+1}$$

$$\text{with} \quad k \in [1, N] \quad \text{and} \quad N^2 = \frac{\gamma P_0 T_0^2}{|\beta_2|} \tag{1}$$

The propagation of a higher order soliton is characterized by a temporal and spectral reshaping (breathing or periodic evolution) after the characteristic length $z_0=\pi/2 \cdot L_D$ [16].. However, the perturbations by higher order dispersion and Raman scattering lead to a fission of that higher order soliton into fundamental solitons with different center wavelengths [14]. The initial creation of the visible components of the continuum is explained by the emission of phase-matched radiation in the normal dispersion region [17]. On the other hand, the fundamental solitons are shifted further to the infrared region due to intrapulse Raman scattering. According to Eq. (1), the peak power of each fundamental soliton is different and so is the frequency shift. Additional frequency shifts occur with further propagation [18]. The overlap of several fundamental solitons and the created linear waves by soliton fission compose the spectrum, which is known as supercontinuum from a photonic crystal fiber.

To discuss the usefulness of the part consisting of linear waves from soliton fission for non-collinear parametric amplification, the recompressibility to ultrashort pulse duration of such a continuum has to be considered. Consequently, a deeper understanding of how these linear waves are created is necessary.

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Primarily, we have to concentrate on the two conditions, which have to be fulfilled to obtain an energy loss from the wavelength of the soliton towards the normal dispersion regime of the fiber. The first one is the phase-matching condition, which can be formulated as [19]:

$$\Delta\phi(\omega)=\phi_r(\omega)-\phi_s(\omega_s)=0 \tag{2}$$

Where $\phi_r(\omega)$ is the phase of the resonant wave at the frequency ω and $\phi_s(\omega_s)$ is the phase of the soliton at the frequency ω_s . These phases can be expressed as:

$$\phi_r(\omega)=n_{eff}(\omega)\cdot\omega\cdot\frac{L}{c}-\omega\cdot\frac{L}{v_s} \tag{3}$$

$$\phi_s(\omega_s)=n_{eff}(\omega_s)\cdot\omega_s\cdot\frac{L}{c}+n_2\cdot I\cdot\omega_s\cdot\frac{L}{2\cdot c}-\omega_s\cdot\frac{L}{v_s} \tag{4}$$

Where $n_{eff}(\omega)$ is the effective refractive index at pulsation ω, c the speed of light, L the propagation length, n_2 is the nonlinear refractive index (n_2=3,2.10^{-20} m^2/W), I is the intensity of the input pulse [W/m^2] and v_s is group velocity of the solitons. The black curve in Fig. 3 shows the calculated phase mismatch (Eq. (2)) for a photonic crystal fiber with a zero dispersion wavelength (ZD) at 975 nm and the following measured (applying spectral interferometry) parameters of the Taylor expansion of the group velocity dispersion: β_2 = -0.01185 ps^2/m, β_3 = 7.995·10^{-5} ps^3/m, β_4 = -1.00392·10^{-7} ps^4/m, β_5 = 1.21005·10^{-10} ps^5/m, β_6 = 4.0347·10^{-14} ps^6/m, ω_0 = 1.7·10^{15} Hz. As shown, the wavelength which is phase-matched to the input wavelength of 1030 nm is around 870 nm. Adding the intensity dependence part of equation 4 to the phase matching condition would lead to a lower phase-matched wavelength [19], however, for simplicity we neglected this part in the calculation of phase-mismatch in Fig. 3. The later herein presented numerical simulations of course include this part.

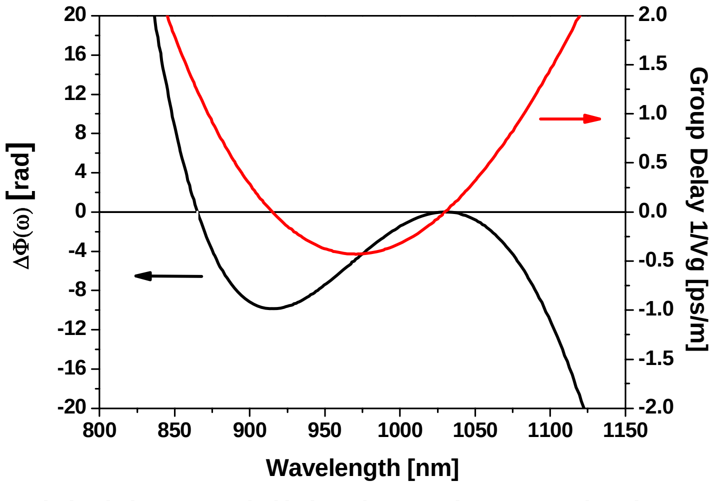

Fig. 3. Calculated phase-mismatch (black) and group velocity mismatch (red) to 1030 nm radiation in the PCF with a zero-dispersion wavelength of 975 nm.

The second condition for the appearance of the resonant emission of linear waves at frequency ω_r is a spectral overlap of the broadened input pulse spectrum to the above described phase-matched wavelength λr. This overlap is obtained by spectral broadening during the initial propagation of the ultrashort pulse, which is primarily equivalent to the initial propagation of a higher order soliton, hence a temporal compression and spectral broadening. Consequently, a certain initial peak power and propagation length in the nonlinear fiber is required. Figure 4 shows a numerical simulation of the spectral evolution during the propagation of a 100 fs pulse with an energy of 300 pJ in 15 cm of PCF with the mentioned dispersion parameters and γ=0.0287/(Wm) (mode field diameter ~ 2.9 µm). The simulation is based on an extended nonlinear Schrödinger equation solved by a split-step Fourier algorithm. As it is shown, as soon as a spectral overlap to phase-matched wavelength region is obtained, energy is transferred to those wavelengths.

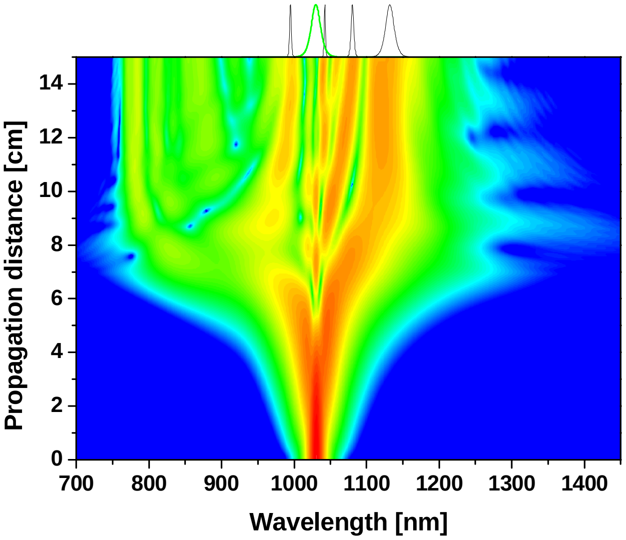

Fig. 4. Duration and energy of the input pulse for this simulated spectral evolution were chosen to create a fourth order soliton so that we can clearly see the breathings behavior [16] and the appearance resonant waves (logarithmic scale 30dB). See text for details of parameters.

From theory it is well known that this resonant emission of linear waves red-shifts the soliton constituents of the initial pulse due to energy conservation even without considering the Raman effect. Of course, this shift is different for the individual solitons given by Eq. (1). If the separation into individual solitons is not completely fulfilled after the first compression and emission of linear waves, repeated spectral compression and broadening similar to the higher order soliton propagation appear. Hence energy is again transferred to linear waves, but at a different position in the fiber and to different wavelength $\lambda_{r'} > \lambda_r$, because of the changed phase-matching (see Fig. 4, and propagation of Fig. 5.).

Furthermore, phase-matched wavelengths do not travel with the same group velocity as the high order soliton inside the fiber, i.e. phase-matching is not equivalent to group delay matching. The group delay mismatch can be formulated as [14]:

$$\Delta\beta_1(\omega) = \beta_1(\omega) - \beta_1(\omega_s) \tag{5}$$

Where $\beta_1(\omega)$ is the group delay at an arbitrary pulsation ω and $\beta_1(\omega_s)$ is the group delay at the soliton wavelength. The group delay mismatch with respect to 1030 nm in the herein discussed PCF with ZD at 975 nm is shown in Fig. 3 (red curve). As it is revealed there is a considerable group delay mismatch at the phase-matched wavelength around 870 nm of more than 1 ps/m. The consequence of this group delay mismatch becomes visible when considering the results of the simulated propagation in a spectrogram view, as shown in Fig.5.

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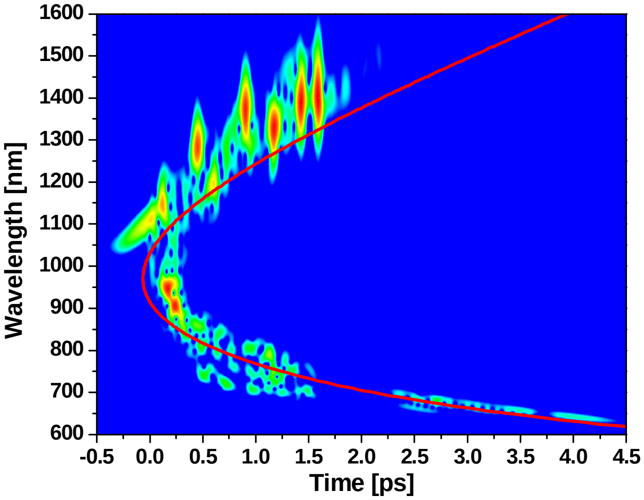

Fig. 5. Initial parameters are chosen in such a way that the simulated spectrogram exhibits several phase jumps. Continuum generated in a 15 cm long PCF with ZDW at 975 nm, input pulse parameters: 150 fs, 1030 nm, 5nJ; red curve: group delay with respect to 1030 nm of the PCF.

One can clearly see the fundamental red-shifted solitons (as also shown in Fig. 4) and the multiple appearances of linear waves. However, time and spectral offsets resulting in phase jumps between the different NSR are noticeable, which are caused by the mechanism of different creation positions and wavelengths of the linear waves mentioned above. Hence, only a rough recompression can be expected even by applying sophisticated dispersion compensation techniques. A high quality phase removal to obtain ultrashort pulse duration, which is actually implied by the broad spectral bandwidth, appears to be impossible. The situation appears to be even worse when considering noise that is potentially included as amplitude noise (even quantum noise) and noise arising from spontaneous Raman scattering. This noise will lead to spectral and temporal fluctuations in the generated supercontinuum and results in a poor recompression quality as the potential compressor will not be able to follow stochastic phase changes from pulse to pulse [20].

The basic idea described herein to overcome this limitation relies on a careful adjustment of the pulse input parameters to create the continuum. By paying attention to peak power injected in the PCF and/or to the length of the fiber, it is possible to excite one single linear resonant wave as depicted in the experimentally obtained spectrum shown in Fig. 6 and calculated in Fig. 7 and 8.

The Fig. 7 and 8 present the theoretical creation and propagation of a continuum composed with a single emission of linear waves and one fundamental soliton. As depicted in Fig. 7 by adjusting the right power in the fiber (moving the focal point out of the fiber front face), the spectrum of the initial high order soliton expands only once to the phase-matched wavelength and a single energy transfer occurs. In that case, we additionally clearly see the red-shift of the fundamental soliton by intrapulse Raman scattering. Both pulses propagate with different velocities leading to a separation in time after propagation in 15 cm length of fiber (Fig. 8).

The idea behind the following experiment is the amplification in an OPCPA stage with further recompression of a single linear wave created by soliton fission. The parametric amplification of spectral region of these linear waves is obtained by adjusting the phase-matching conditions and time delay between pump and signal in the OPCPA stage. Due to the monotonic chirp of the single linear wave, it can be readily recompressed to ultrashort pulse duration with standard dispersive elements such as a prism sequence.

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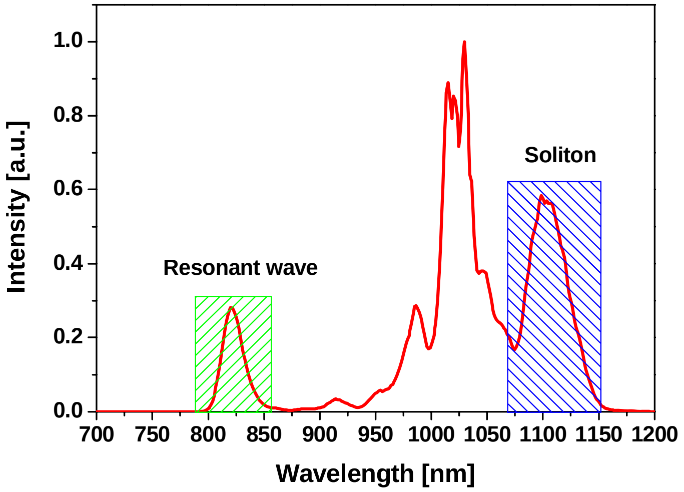

Fig. 6. Experimental spectrum with a single resonant wave and soliton created in a 15cm long PCF fiber with ZDW = 975 nm, input pulse parameters: 50 fs, 1030 nm, 350pJ.

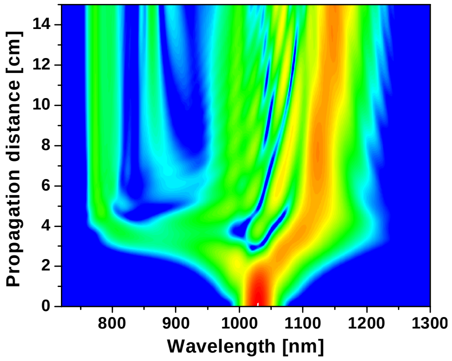

Fig. 7. Spectral evolution of a 2nd order soliton propagating in a 15 cm long fiber, input pulse parameters: 50 fs, 1030 nm, 350pJ, N=3.

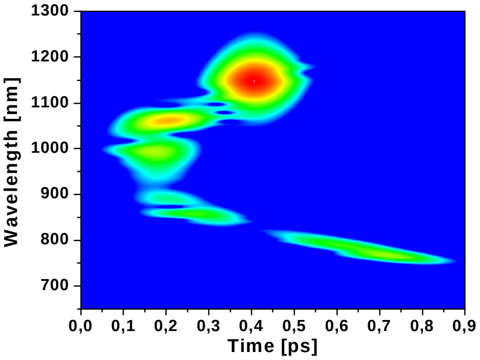

Fig. 8. Spectrogram of a continuum with the same parameters as Fig. 7.

3. Experiment and Results

The setup of the ultrashort pulse parametric amplification system, which employs a fiber based signal and pump pulse generation is shown in Fig. 9.

The pump source consists of a high repetition rate fiber based chirped pulse amplification (CPA) system. A rare-earth-doped fiber is the predestinated gain architecture for high average power short pulse amplification. This fact has its origin in the excellent heat dissipation capabilities and the confinement of the laser radiation in waveguide structures. Hence, a immunity against thermo-optical problems is provided and a power independent diffraction-limited beam quality can be extracted [21]. As master oscillator a passively mode-locked Yb:KGW laser (Amplitude Systemes tpulse200) is used. This laser is delivering transform-limited 420 fs sech^2 pulses at a repetition rate of 9.8 MHz and pulse energies up to 250 nJ at a center wavelength of 1030 nm. An acousto-optical modulator (AOM) is used to reduce the repetition rate to 1 MHz. Half of the energy is sent to the stretcher, which increases the pulse duration to 80 ps. The stretched pulses are amplified in a low-nonlinearity large-mode-area photonic crystal fiber [22]. This fiber possesses a 40 µm intrinsically single-mode ytterbium-doped core and an inner-cladding with a diameter of 170 µm (NA ~ 0.6). The pump absorption at 976 nm is as high as 16 dB/m, hence, just a fiber length of 1.2 m is used in the amplification stage. The fiber amplifier produces an average power of up to 10 W, corresponding to 10 µJ pulse energy. A grating pair compresses the amplified and stretched pulse to 750 fs duration with a throughput efficiency of ~60%. Finally, these pulses are frequency-doubled in a 1 mm long BBO crystal which is cut for type 1 phase-matching. A conversion efficiency of about 50% results in up to 3 W of average power at 515 nm wavelength. Based on measured autocorrelation traces of the infrared pulses and calculations done with the freely available SNLO software [11], the pulse duration of the second harmonic (SH) can be estimated to be 770 fs.

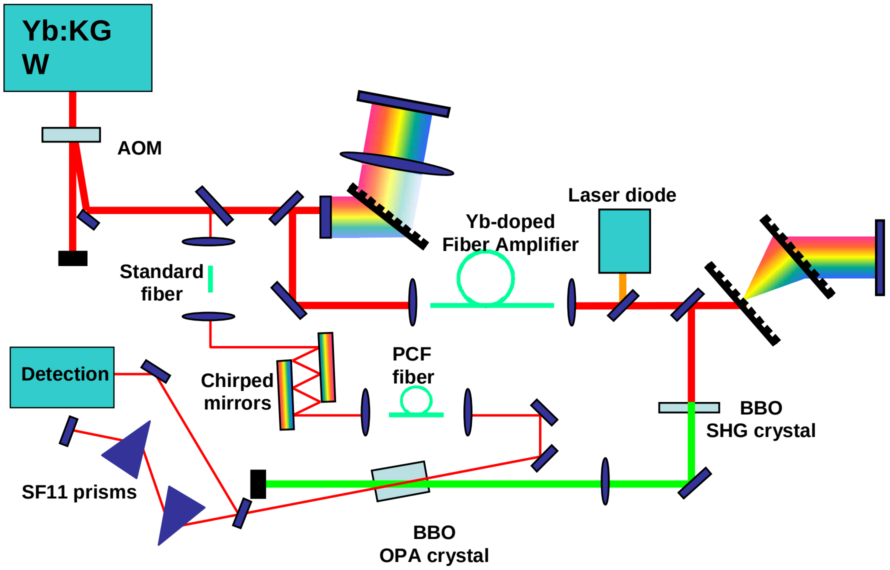

Fig. 9. Experimental setup of the short pulse parametric amplification system, PCF photonic crystal fiber, BBO: beta barium borate crystal.

The second half of optical power contained in the diffracted order of the AOM is used for signal generation for the OPA stage. As described above, PCF dispersion characteristics and input pulse parameters determine the spectral characteristics of the emitted continuum. Consequently, due to fixed dispersion parameters of the nonlinear fiber and fixed center wavelength of the short pulse oscillator the peak power and pulse duration at the input of the PCF have to be adjusted to obtain a desired spectrum. In general, a spectrum as shown in Fig. 6 featuring just one linear wave and soliton emission can be generated by launching 420 fs long pulses from the oscillator by carefully controlling the input power. However, we have chosen to shorten the pulse duration before the continuum generation, thus, according to equation (1) the soliton order is reduced. Hence, more power can be launched into the PCF (and finally is available as signal for the OPA stage) to obtain similar soliton dynamics as with longer pulses resulting in a single soliton emission, what we have identified as a precondition for the compressibility to ultrashort pulse duration.

Nonlinear pulse compression is applied to reduce the pulse duration before the highly nonlinear PCF. An average power of 60 mW is launched into a 4.5 cm long standard step-index fiber with a mode field diameter of 6.6 µm at 1030 nm. The spectrum is broadened to 70 nm bandwidth due to self-phase modulation. A pair of chirp mirrors providing a chirp of -250 fs^2 per bounce is used to compress the pulses. A pulse duration of 50 fs is obtained with 20 bounces. It has to be pointed out that this pulse pre-compression is only done to provide a higher input power for the OPA, in general also longer pulses can be used.

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A small fraction of the pre-compressed pulses (about 350 µW, corresponding to 350 pJ) are coupled into a 15 cm long PCF possessing a 3 µm core and a zero-dispersion wavelength of 975 nm. The emitted continuum is shown in Fig. 6. Approximately 30 µW of average power are contained in the single linear wave emitted around at 870 nm. This part of the spectrum is used as the signal for the OPA having a high spectral density and an excellent spatial beam profile. Due to its bandwidth this part is stretched in time to about 320 fs by the residual length of the PCF. This allows for a temporal matching to the pump pulses and, therefore, an efficient amplification in the OPA stage.

Besides the well known benefits of parametric amplification of ultrashort laser pulse, such as the high gain, the enormous bandwidth and the negligible thermal load [23,24], there is one more important aspect making the combination of parametric amplifiers and fiber amplifiers attractive. In general, the performances of short pulse fiber amplifiers are limited by nonlinear pulse distortion [21, 22]. Indeed, self-phase modulation induces a nonlinear phase. Hence, the fiber based generation of high peak power transform-limited pulse remains difficult. At contrast, in a parametric amplifier the phase of the pump field is transferred to the idler field [24]. Consequently, the phase of the amplified signal is not distorted allowing for high quality phase compensation and the generation of ultrashort laser pulse even in the case of a distorted pump.

Finally, the continuum and the SH at 515 nm are overlapped non-collinearly in a 5 mm long BBO crystal (type I) and temporal overlap is obtained by means of a delay stage. The SH beam is focused to a spot-size of roughly 100 µm, which enables peak-intensities of up to 70 GW/cm^2 while ensuring a proper spatial overlap with the seed. A non-collinearity angle (angle between pump and signal) of 2.6° is adjusted to the "magic" phase-matching condition as shown in Fig. 1. The phase-matched bandwidth perfectly overlaps the spectral range of the single linear wave generated in the PCF, which is in our configuration typically emitted between 800 and 900 nm.

At a pump power of 1.7 W the signal at 870 nm is amplified to 50 mW average power in the 5mm BBO crystal. The amplified spectrum extends over 25 nm (FWHM) as shown in Fig. 10. Using a pair of SF11 prisms, the duration could be decreased from the initial 350 fs down to 55 fs assuming a Gaussian pulse shape (80 fs autocorrelation width). The measured autocorrelation trace is shown in Fig. 11. The high quality of the compressed pulses confirmed the monotonic chirp of the linear waves created under the described conditions.

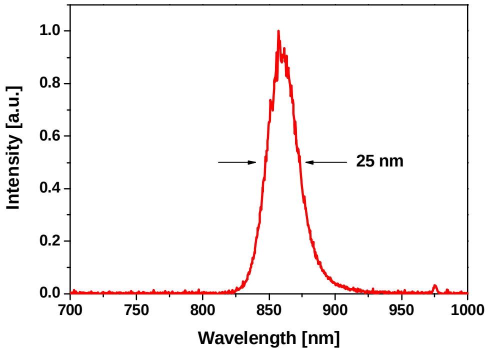

Fig. 10. Spectrum of parametrically amplified lower wavelength part of the supercontinuum.

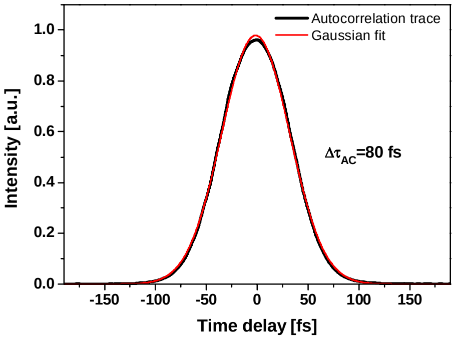

Fig. 11. Measured autocorrelation trace of amplified and recompressed pulse.

The obtained results have to be considered as a proof-of-principle, however, they are revealing a very promising way to create energetic short optical pulses using parametric amplification of resonant waves. Increasing the number of parametric stages we will be able to conserve phase characteristics and and spectral distribution of the amplified pulses while improving their energy. Performance up-scaling relies on enhanced output energies of the fiber based CPA system. Such fiber based short pulses sources have the potential for pulse energies of ~1 mJ at repetition rates in the 100 kHz to 1 MHz range and sub-picosecond pulse duration [21]. Assuming a conversion efficiency of >10% to NOPA wavelengths (>50% SHG, >20 % OPA process), we can expect >100 µJ at the output of the fiber laser pumped NOPA system. On the other hand, significantly shorter pulses are possible by optimization of the generation of the resonant linear wave. It has been shown that the bandwidth of the resonant linear wave depends strongly on the chirp of the input pulses [25]. Therefore, applying the reported signal generation approach together with an optimized OPA setup the generation of sub 20 fs pulses with energies of >100 µJ at >100 kHz repetition rate, corresponding to >5 GW peak power, appears to be feasible. Such parameters will open the door of high field physics at high repetition rates.

4. Conclusions

To summarize, we have presented a novel approach to tailor light pulses specifically designed to provide a fiber based signal for an ultrashort pulse optical parametric amplifier. Starting from a detailed discussion of continuum generation, conditions have been identified on how a continuum from a photonic crystal fiber has to be generated to achieve a signal, which is recompressible to ultrashort pulse duration.

Experimentally, the parametric amplification of single linear wave created by soliton fission has resulted in the generation of 55 fs at 1 MHz repetition rate at a center wavelength of 870 nm. It has to be emphasized that the initial pulse duration of the mode-locked oscillator is as long as 420 fs. The approach is power scaleable due to the use of a fiber laser system as pump source.

In the future, we intend to increase the extracted pulse energy by adding a second OPA stage and by increasing the pulse energy of the pump source. Furthermore, we will investigate the potential of reduction of pulse duration of the described approach. We are convinced that the described approach has the potential to generate sub-20 fs pulses at high repetition rates (~MHz) and with high pulse energies (>100 µJ). Moreover, the simplicity and stability of the setup and the potential for power scaling makes this system an interesting alternative to traditional Ti:Sapphire based NOPA-schemes and will find numerous applications in spectroscopy and high field physics.

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