Linear compression of chirped pulses in optical fibre with large step-index mode area

S. V. Smirnov, S. M. Kobtsev*, and S. V. Kukarin

Division of Laser Physics and Innovative Technologies, Novosibirsk State University, Pirogova str., 2, Novosibirsk 630090, Russia

*kobtsev@lab.nsu.ru

Abstract: The possibilities and limitations of linear compression of positively chirped pulses in the negative-dispersion region of a step-index large mode-area single-mode optical fibre are investigated for the first time. Analytical formulae for critical values of radiation power are found, below which pedestal-free pulse compression is possible down to the Fourier limit. It is demonstrated that at radiation powers exceeding these critical values, there exists an optimal compressing fibre length, over which laser pulses reach the minimum of the time-bandwidth product, and beyond which irreversible pulse deformation occurs. The modelling results agree well with the experimental data.

OCIS codes: (320.5520) Pulse compression; (140.3510) Lasers, fiber; (060.2310) Fiber optics.

References and links

1. N. Akhmediev and A. Ankiewicz, *Dissipative solitons* (Springer, 2005).
2. B. Ortaç, M. Plötner, J. Limpert, and A. Tünnermann, "Self-starting passively mode-locked chirped-pulse fiber laser," Opt. Express **15**(25), 16794–16799 (2007).
3. W. H. Renninger, A. Chong, and F. W. Wise, "Giant-chirp oscillators for short-pulse fiber amplifiers," Opt. Lett. **33**(24), 3025–3027 (2008).
4. D. Strickland and G. Mourou, "Compression of amplified chirped optical pulses," Opt. Commun. **56**(3), 219–221 (1985).
5. R. Won, "Chirped pulse amplification: Similariton seeding," Nat. Photonics **6**(11), 716–717 (2012).
6. L. F. Mollenauer, R. H. Stolen, and J. P. Gordon, "Experimental observation of picosecond pulse narrowing and solitons in optical fibers," Phys. Rev. Lett. **45**(13), 1095–1098 (1980).
7. D. Grischkowsky and A. C. Balant, "Optical pulse compression based on enhanced frequency chirping," Appl. Phys. Lett. **41**(1), 1–3 (1982).
8. J. M. Wiesenfeld and J. Stone, "Chirp in picosecond film lasers and pulse compression by linear dispersion in optical fibers," Opt. Lett. **8**(5), 262–264 (1983).
9. K. Tamura, E. P. Ippen, H. A. Haus, and L. E. Nelson, "77-fs pulse generation from a stretched-pulse mode-locked all-fiber ring laser," Opt. Lett. **18**(13), 1080–1082 (1993).
10. L. Chusseau and C. Kazmierski, "Optimum linear pulse compression of a gain-switched 1.5/spl mu/m DFB laser," IEEE Photon. Technol. Lett. **6**(1), 24–26 (1994).
11. H. Hundertmark, *Erbium fiber lasers for a frequency comb at 1560 nm* (Cuvillier, 2006).
12. D. Deng, L. Zhan, Z. Gu, Y. Gu, and Y. Xia, "55-fs pulse generation without wave-breaking from an all-fiber Erbium-doped ring laser," Opt. Express **17**(6), 4284–4288 (2009).
13. B. Nikolaus and D. Grischkowsky, "12X pulse compression using optical fibers," Appl. Phys. Lett. **42**(1), 1–2 (1983).
14. M. F. Ferreira, *Nonlinear effects in optical fibers* (Wiley-OSA, 2011).
15. G. P. Agrawal, *Nonlinear fiber optics* (Academic, 2012).
16. Nufern, 25/250 Precision Matched Passive LMA Double Clad Fiber, *http://www.nufern.com/pam/optical_fibers/1082/LMA-GDF-25_250-M/*
17. nLIGHT, Passive-25/250DC-PM, *http://www.nlight.net/nlight-files/file/datasheets/Fibers/nLIGHT_LIEKKI-Passive-Fibers_110214.pdf*
18. N. K. T. Photonics, LMA-25 Single-Mode 25μm Core Fiber, *http://www.nktphotonics.com/files/files/LMA-25.pdf*
19. N. G. R. Broderick, H. L. Offerhaus, D. J. Richardson, R. A. Sammut, J. Caplen, and L. Dong, "Large mode area fibers for high power applications," Opt. Fiber Technol. **5**(2), 185–196 (1999).
20. T. Südmeyer, F. Brunner, E. Innerhofer, R. Paschotta, K. Furusawa, J. C. Baggett, T. M. Monro, D. J. Richardson, and U. Keller, "Nonlinear femtosecond pulse compression at high average power levels by use of a large-mode-area holey fiber," Opt. Lett. **28**(20), 1951–1953 (2003).

21. S. Hädrich, J. Rothhardt, T. Eidam, J. Limpert, and A. Tünnermann, "High energy ultrashort pulses via hollow fiber compression of a fiber chirped pulse amplification system," Opt. Express **17**(5), 3913–3922 (2009).
22. M. Li, X. Chen, A. Liu, S. Gray, J. Wang, D. T. Walton, and L. A. Zenteno, "Effective Area Limit for Large Mode Area Laser Fibers," in *Optical Fiber Communication Conference/National Fiber Optic Engineers Conference*, OSA Technical Digest (Optical Society of America, 2008), paper OTuJ2.
23. M. Horowitz, Y. Barad, and Y. Silberberg, "Noiselike pulses with a broadband spectrum generated from an erbium-doped fiber laser," Opt. Lett. **22**(11), 799–801 (1997).
24. S. Kobtsev, S. Kukarin, S. Smirnov, S. Turitsyn, and A. Latkin, "Generation of double-scale femto/pico-second optical lumps in mode-locked fiber lasers," Opt. Express **17**(23), 20707–20713 (2009).

1. Introduction

One of the most frequently used ways to generate ultra-short laser pulses is linear dispersion compression (by means of external dispersion elements) of pulses with nearly monotonic frequency chirp coupled out of a laser cavity or an optical amplifier. For example, pulses having close to linear positive chirp may be obtained both from a fibre oscillator with a net-normal-dispersion cavity [1–3] and from an amplifier using chirped pulse amplification technique [4, 5], which allows lowering peak power of pulses due to their temporal stretching prior to their entering the amplifier. Methods of linear dispersion compression are then used to compress such pulses with optical elements having negative chromatic dispersion. This function may be performed by a variety of optical components, both discrete (diffraction or Bragg gratings, prisms, chirped mirrors, &c) and fibre-based, including specialty fibres (such as gas-filled hollow-core fibres, holey fibres, dispersion-decreasing, and other types of fibres). Within the spectral domain around 1.5 μm, linear temporal compression of positively chirped pulses may be done with a conventional single-mode optical fibre (for instance, SMF-28) having negative chromatic dispersion and close to linear group-velocity dispersion slope in this spectral range. This possibility was earlier experimentally demonstrated using a single-mode optical fibre with a standard mode area [6–12]. However, standard single-mode fibres with relatively small mode area exhibit correspondingly low non-linear effect threshold, not permitting pure linear dispersion compression even at average radiation powers as low as several tens of mW in picosecond pulses following at a megahertz repetition rate [13–15].

In recent years, significant progress in optical fibre manufacturing led to commercial availability of optical fibres with large mode areas (LMA), often featuring support of a single transverse mode. Mode field area in such fibres [16–18] may exceed that of standard telecom single-mode fibres by up to an order of magnitude, thus allowing substantially lower radiation power density in LMA fibres and, consecutively, much higher non-linear effect threshold.

Nevertheless, even though LMA fibres feature a relatively high non-linear effect threshold, until the present study, they were only used for non-linear compression of pulses with high energy or peak power allowed in a relatively large core of these fibres [19–21]. It is equally pertinent to note that LMA fibres hitherto used for pulse compression have elaborate structure (holey fibre or noble-gas-filled hollow fibre) complicating their splicing to standard optical fibres, whereas step-index LMA fibres may be easily coupled to conventional single-mode fibres.

In the present work, we explore for the first time both theoretically and experimentally possibilities and limitations of linear compression of positively chirped pulses in the negative-dispersion region of a step-index single-mode optical fibre with core size of 25 μm, which is close to the physical limit for single-mode operation [22]. Interest in this type of temporal pulse compression stems from the fact that step-index LMA-fibre-based linear compressor complies with the concept of all-fibre configuration and may be simply welded to the output fibre of an all-fibre master oscillator or fibre amplifier. Here, we have found out the critical peak radiation power up to which pedestal-free Fourier-limited temporal pulse compression is possible in a linear compressor using a step-index LMA fibre with the core size close to the maximum yet supporting single-mode performance. We also discovered that at power levels exceeding the critical value, there exists an optimal fibre length over which laser pulses reach a minimum (although not the physically possible minimal value) of the time-bandwidth product (TBP), thereafter undergoing an irreversible deformation.

2. Experiment

The experimental installation is schematically shown in Fig. 1(a). We used a net-normal-dispersion erbium fibre laser passively mode-locked via a saturable semiconductor absorber as the master oscillator. The laser generated a pulse train at the repetition rate of 48 MHz (also 32 MHz or 16 MHz, depending of the setting of polarisation controller PC and the pumping radiation power) at the wavelength of 1,560 nm and the average output power of 5 mW. The output pulses had a spectrum with a typical Π-shape (Fig. 1(b)) and a 12-nm width corresponding to a ~210-fs spectrally limited pulse with a sech^2 envelope. FWHM of the recorded pulse auto-correlation function (ACF) was 5 ps (Fig. 1(c)), indicating half-magnitude duration of sech^2 pulses around 3.2 ps and therefore, significant chirp.

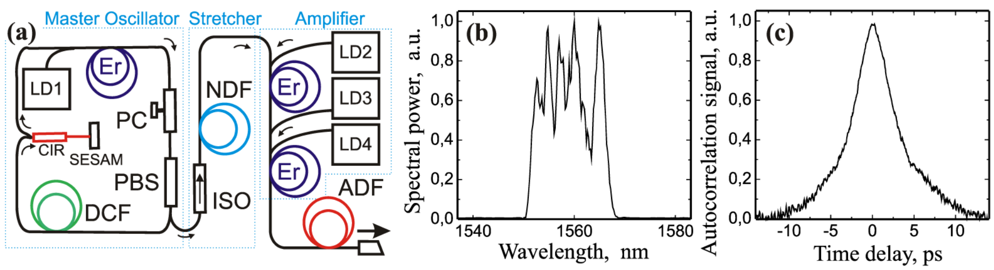

Fig. 1. (a) All-fibre laser system schematic diagram. LD – laser diode pump, Er – Er-doped active fibre, PC – polarisation controller, PBS – polarisation beam splitter, CIR – 3-port circulator, SESAM – semiconductor saturable absorber, ISO – optical isolator, DCF – passive double-clad fibre, NDF – normal-dispersion fibre, ADF – anomalous-dispersion fibre (LIEKKI Passive-25/250); (b), (c) Spectrum and auto-correlation function of pulses at the output of the master oscillator.

Further on, these pulses were boosted to 1 W of average power in a fibre amplifier having a 20-μm core. In order to minimise spectral and temporal distortion of the pulses in the process of amplification, before entering the amplifier, pulses from the master oscillator were temporally stretched in a 112-m fibre with normal dispersion $D = -4$ ps/nm/km ($\beta_2 = 5.2$ ps^2/km) and a 8-μm core. Stretched pulse width amounted to about 10 ps and did not change after amplification. For temporal compression, pulses exiting the amplifier were passed through a step-index LMA fibre (LIEKKI Passive-25/250) with a 25-μm core, NA = 0.07, and anomalous dispersion $\beta_2 = -17.5$ ps^2/km. The length of the LMA fibre was selected so as to produce the shortest possible output pulses. At the average radiation power of radiation exiting LMA fibre up to 120 mW, the optimal fibre length corresponded to temporal pulse compression down to 250 fs, *i.e.* close to the Fourier limit. The pulse auto-correlation function (see Fig. 2(a)) had a smooth shape close to that of a two-sided exponential function.

As the average radiation power was raised above 120 mW at the repetition rate of 48 MHz, optical spectrum broadened slightly and a characteristic narrow peak emerged in the centre of the ACF on a broader pedestal [23, 24], suggesting that laser pulse break-up occurred in the fibre compressor and stochastically filled pulse trains were forming (Fig. 2(b)). It is also interesting to observe that relatively high (~1 W) average radiation powers led to an ACF shape very close to pedestal-free (see Fig. 2(c)). This was the result of a very low pedestal, which was hardly distinguishable against the noise background. Quite unexpectedly, it turned out that a substantial proportion of the pulse energy was spread along this barely visible and broad pedestal. This circumstance was established in our experiments on second harmonic generation using these compressed pulses. A low amount of energy corresponding to the narrow peak of auto-correlation function is corroborated by substantially lower second harmonic generation efficiency of such pulses compared to analogous efficiency of laser

#228575 - $15.00 USD Received 25 Nov 2014; revised 30 Jan 2015; accepted 3 Feb 2015; published 9 Feb 2015

pulses with similar duration compressed by two diffraction gratings. This false appearance of "good" pulse compression in an LMA fibre at relatively high average radiation powers also resulted from the fact that the width of the narrow peak sitting on top of an extremely broad and hardly noticeable pedestal happened to be approximately 200 fs, which is very close to the duration of Fourier limited pulse calculated from the radiation spectrum (~210 fs).

It was namely the observed illusion of "good" pulse compression in optical fibre with step-index large mode area at comparatively high average incident powers (around and exceeding 1 W) that gave rise to research reported in the present paper.

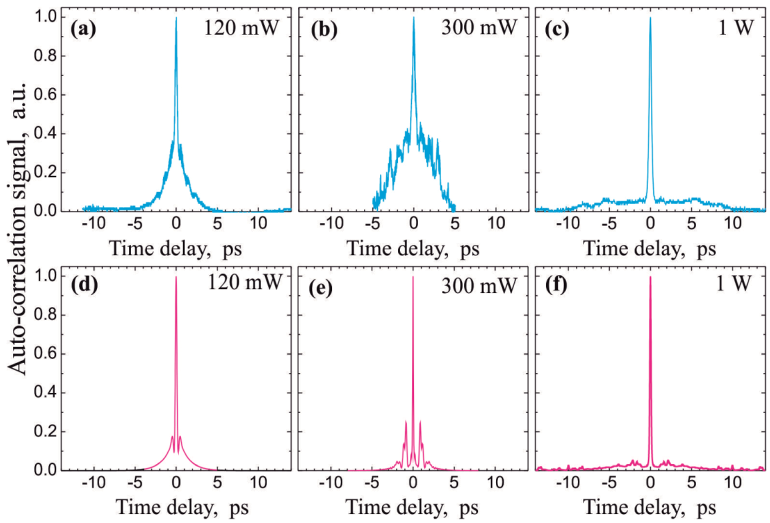

Fig. 2. Measured (a–c) and simulated (d–f) auto-correlation function of compressed pulses at different levels of the average radiation power (P_{avg} is shown in each plot).

3. Numerical modelling

To study temporal compression of laser pulses in optical fibre, we utilised the non-linear Schrödinger equation [15] for the complex field envelope A:

$$\frac{\partial A}{\partial z} = -\frac{i}{2}\beta_2 \cdot \frac{\partial^2 A}{\partial t^2} + i\gamma |A|^2 A \quad (1)$$

where z is the longitudinal coordinate, t – time, $\gamma = 0.2 \times 10^{-5}$ (cm·W)$^{-1}$, $\beta_2 = -17.5$ ps^2/km are non-linearity and dispersion for compressor anomalous-dispersion fibre (ADF) (β_2 = 5.2 ps^2/km is dispersion of the stretcher fibre). For the initial conditions for integration of Eq. (1), we used a positively chirped sech^2 pulse, which is a good approximation of numerical solutions of equations describing formation of dissipative solitons in lasers with normal dispersion.

$$A(t,0) = P_0^{1/2} \cosh^{-1}\left(\frac{t}{T_0}\right) \cdot \exp\left(-i\frac{a}{b} \cdot \ln\cosh bt\right) \quad (2)$$

where P_0 is peak power, T_0 – duration parameter ($T_0 = 0.567 \times T_{FWHM}$); a, b – spectrum width and frequency modulation parameters. Pulse (2) has non-linear chirp which can be linearised near the centre of the pulse $C = T_0^2 \cdot d^2(-\arg A)/dt^2 = abT_0^2$.

Equation (1) was integrated numerically with initial conditions (2) by means of the step-split Fourier method up to the critical point z_{max}, in which either the pulse decays or its linear chirp reaches the value of 0 (depending on which of the events happens first). The adopted

#228575 - $15.00 USD Received 25 Nov 2014; revised 30 Jan 2015; accepted 3 Feb 2015; published 9 Feb 2015

model describes our experimental observations reasonably well at different power levels up to the pulse decay. At higher powers, which only appear in Fig. 2(e), 2(f) and nowhere else in this work, we used the generalised non-linear Schrödinger equation, which includes third-order dispersion, Raman term and self-steeping effect [15]. Numerical results obtained in these two models at relatively small average radiation powers (up to 150 mW) coincide.

The parameters of the initial pulse (2) were varied by an order of magnitude around their average values corresponding to the experiment (the latter were estimated as T_0 = 1.8 ps, a = 4.65 ps^{-1}, $b \sim 1/T_0$ = 0.55 ps^{-1}, C ~8.5). It was established that in the process, the maximal non-linear phase incursion in the centre of the pulse $\varphi_{\max}$, above which pulse decay occurs, only varied by half an order (by a factor of ~6 to 18). This result allows a simple estimate of the limit on the power of sech^2 laser pulses in optical fibre with anomalous dispersion. Indeed, let us consider strongly chirped pulses of initial duration T_0 and spectral width $\Delta\omega$. We will assume the pulse power sufficiently low and the initial pulse chirp sufficiently strong. In this case, it is possible to say that $T(z) = T_0 - qL|\beta_2|\Delta\omega$, where q is a proportionality coefficient depending on the pulse shape (q = 1.151 for pulses of type (2)). Length L_1 of compressing fibre can be determined from the condition of linear temporal compression to the Fourier limit:

$$T_0 - q \cdot |\beta_2| \Delta\omega \cdot L_1 = \kappa / \Delta\omega \quad (3)$$

Where κ is the Fourier limit, whose numerical value is different for pulses of different shape. Taking into account the fact that the product of peak power and duration of a pulse in the process of compression is approximately conserved, one can derive an expression for pulse's non-linear phase incursion in a fibre of length L_1 required for linear pulse compression:

$$\delta\varphi_{NL} = \gamma P_0 \cdot \int_0^{L_1} \frac{T_0\, dz}{T(z)} = \frac{\gamma P_0 T_0}{q|\beta_2|\Delta\omega} \ln \frac{T_0 \Delta\omega}{\kappa} \quad (4)$$

Assuming from the numerical modelling results that $\delta\varphi_{NL} = \varphi_{\max}$ ~12, which means that pulse decay occurs on the same length L_1 as required for linear pulse compression down to Fourier limit, we can obtain the limit on the maximal radiation peak power P_0 and on the related to it maximal average power P_{avg}:

$$P_0 = \frac{q\,\varphi_{\max} D\Delta\lambda\tau^{-1}\gamma^{-1}}{\ln\left[2\pi c\tau\Delta\lambda/(\kappa\lambda^2)\right]} \approx \frac{14\, D\Delta\lambda\tau^{-1}\gamma^{-1}}{\ln\left[2c\tau\Delta\lambda/\lambda^2\right]},\ P_{\text{avg}} = \frac{\nu\alpha\, q\,\varphi_{\max} D\Delta\lambda\gamma^{-1}}{\ln\left[2\pi c\tau\Delta\lambda/\kappa\lambda^2\right]} \approx \frac{10\nu D\Delta\lambda\gamma^{-1}}{\ln\left[2c\tau\Delta\lambda/\lambda^2\right]} \quad (5)$$

Here $\tau = 1.55\ T_{\text{FWHM}} = 2.732\ T_0$ is the half-magnitude width of ACF pulses (2), ν = 48 MHz is the laser pulse repetition rate, $\Delta\lambda$ = 12 nm, and λ = 1,560 nm are spectrum width and wavelength correspondingly, c – speed of light in vacuum, $D = -2\pi c\beta_2/\lambda^2$ = 13.55 ps/km/nm and γ = 0.2 (km·W)$^{-1}$ are dispersion and non-linearity of the fibre. When deriving Eq. (5), it was taken into account that for pulses of type (2) energy $W = \alpha P\tau$, where α = 0.732, q = 1.151, TBP $\kappa = \tau \times \Delta\omega = 2\pi \times 0.315 \times 1.55 = 3.067$, and $D\Delta\lambda \sim -\beta_2\Delta\omega$. For the parameters of our set-up listed above, expressions (5) yield P_0 < 330 W and P_{avg} < 120 mW, demonstrating a good agreement with the experimental data.

4. Results and discussion

Estimations (5) obtained here allow drawing certain conclusions about possible ways to raise the maximal power of compressed pulses in a single-segment linear fibre compressor. First of all, in order to increase the average power of amplified pulses P_{avg}, initial pulses with broader spectra and higher repetition rates should be used, as well as compressing fibres with higher dispersion and lower non-linearity. Further, let's note that the expressions of Eq. (5) depend weakly (logarithmically) upon the initial pulse duration τ, therefore the length of stretching fibre in front of the amplifier only slightly affects P_0 and P_{avg}. Nevertheless, excess stretching fibre necessitates a correspondingly longer compressing fibre, thus increasing the system non-linearity and therefore reducing P_0 and P_{avg}. For instance, increasing τ from 5 to 10 ps in the stretching fibre effectively reduces P_0 and P_{avg} by about 20% in our experimental set-up.

In case of laser pulse power exceeding the critical values defined by Eq. (5), pulses cannot be compressed down to the Fourier limit in a compressing fibre. During an initial propagation stage of such pulses, their duration shortens and their peak power correspondingly grows. When the non-linear phase incursion exceeds the critical value, the pulse decays and its spectrum is rapidly broadened (initial stage of super-continuum generation). TBP of the pulse monotonically diminishes almost up to the point of decay, upon which it starts growing again because of the widening spectrum. Therefore, there is an optimal length of the compressing fibre L_{opt}, which minimises TBP at a given level of the pulse power. Optimal length L_{opt} may be easily estimated from the condition of equality of non-linear phase incursion $\varphi_{NL} = \int \gamma P dz$ and the critical phase value φ_{max}:

$$L_{opt} = \frac{\tau}{qD\Delta\lambda} \cdot \left[1 - \exp\left(-\frac{qD\Delta\lambda}{\gamma P_0 \tau} \varphi_{max} \right) \right] \quad (6)$$

At low levels of P_0, optimal fibre length L_{opt} approaches the value of L_1 from Eq. (3), and at higher powers, L_{opt} is progressively reduced because the compressed pulse decays over a shorter travel through the fibre. For the experimental set-up studied in the present work, $L_{opt}(P_{avg.max} = 120 \text{ mW}) = 50$ m. As the average power of radiation pulses is increased, for example, to $P_{avg} = 1$ W ($P_0 = 2.8$ kW), we obtain $L_{opt} = 17$ m, which is only about 1/3 of the length needed for linear pulse compression.

5. Conclusion

The conducted studies have revealed possibilities and limitations of linear compression of positively chirped pulses in the negative-dispersion region of a step-index LMA optical fibre with core size of 25 µm, which is close to the physical limit for single-mode operation. Both theoretically and experimentally we found critical values of radiation power, below which pulses may be compressed down to the Fourier limit. For the used experimental installation, the critical peak pulse power was 0.33 kW, which corresponds to the average power of 120 mW. At power values exceeding these critical figures, temporal compression is only possible to a lesser degree (not down to the physically possible minimum of the TBP) over the optimal length of the compressing fibre defined by Eq. (6). Compressing fibre with the length exceeding this optimal value results in irreversible deformation of input pulses. It is relevant to note that the analytical expressions for critical radiation power and optimal length of compressing fibre identified in the present work are valid for any fibres used in linear compression of chirped pulses.

Acknowledgments

This work was supported by the Grants of Ministry of Education and Science of the Russian Federation (agreement No. 14.B25.31.0003, order No 3.162.2014/K and 2419 (ZN-06-14)); Council of the Russian President for the Leading Research Groups (project No. NSh-4447.2014.2).