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Use of heavily doped germanosilicate fibres with a small core diameter in stretchers of ultrashort laser pulses at a wavelength of 1.03 μm

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Abstract. **The use of a heavily doped germanosilicate fibre with a W-profile refractive index and small core diameter in stretchers of ultrashort laser pulses with their subsequent amplification and compression in all-fibre laser systems is considered. The application of fibres of this type makes it possible to stretch, amplify, and then compress a laser pulse with minimum distortions of its initial shape and width. Due to the dispersion properties of these fibres, which allow the pulse duration to be increased significantly at a small fibre length and the third-order positive dispersion of the diffraction-grating-based output compressor to be compensated for, amplified pulses with an energy of 2 μJ and width of 250 fs, free of a picosecond pedestal, are obtained. Several types of fibres intended for the use in stretchers of ultrashort laser pulses are comparatively analysed from the point of view of their dispersion compatibility with a diffraction-grating-based output compressor.**

Keywords: *fibre lasers, femtosecond lasers, amplification of ultrashort laser pulses, nonlinear self-phase modulation, group-velocity dispersion, heavily doped germanosilicate fibre.*

1. Introduction

Compact, reliable and mobile femtosecond laser sources with an output pulse energy of several units or tens of microjoules, operating at a wavelength of 1 μm with a high pulse repetition rate (PRR), are greatly demanded in fine materials processing, sensing, and ophthalmology (laser correction of eyesight and cataract removal) [1]. The most efficient instruments for these applications are pulsed (femtosecond and subpicosecond) fibre laser sources with a PRR up to 1 MHz or higher, which provide desired output characteristics and, simultaneously, have high reliability and simple design. One of the conditions for successful application of these pulsed sources in fine materials processing is the high pulse contrast (ratio of the femtosecond pulse and broadened pedestal energies). A low pulse contrast leads to an increase in the photoconversion thresholds and undesirable heating of the irradiated region.

The three main problems that arise when studying fibre amplifiers of ultrashort laser pulses are as follows: (i) influence of uncompensated higher order dispersion on the shape and spectrum of the amplified pulse; (ii) nonlinear self-phase modulation (SPM) of a pulse, which occurs during its amplification; and (iii) Raman scattering of a high-power pulse in a fibre. The main methods allowing one to amplify ultrashort pulses in a fibre without any significant changes in their shape and spectrum include parabolic amplification [2, 3], compensation for the third-order dispersion with nonlinear SPM [4, 5], and amplification of chirped laser pulses [6–8]. Parabolic amplification with proportional changes in the temporal and spectral characteristics of a pulse does not make it possible to obtain amplified pulses with energies above 1 μJ because of the limitation of the fibre amplifier bandwidth [9]. To compensate for the third-order dispersion with nonlinear SPM, one must provide exact correspondence between several parameters: fibre lengths, gain, and pulse spectral characteristics, a circumstance hindering application of this method beyond laboratory conditions.

The method of chirped-pulse amplification suggests the use of a pulse stretcher, which is installed before the fibre power amplifier to attenuate the power density transmitted through the amplifying fibre, thus reducing the influence of SPM on the shape and spectrum of the amplified pulse. After being stretching and amplifying, pulses are finally subjected to compression to their initial width in the compressor. A compressor composed of two diffraction gratings, which allows one to control the compression coefficient in wide limits, is more popular as compared with other versions (more complex technologically). Examples of the latter are a laser pulse compressor based on a segment of photonic-crystal fibre [10] and a compressor based on a volume diffraction grating [11], which are characterised by a fixed compression coefficient.

The possibility of amplifying a pulse without distortion of its initial shape depends in many respects on the dispersion compatibility of the stretcher and compressor. The dispersion of both second and third orders in fibre systems at a wavelength of 1 μm is generally positive. The second-order dispersion in an output compressor based on diffraction gratings is negative, while the third-order dispersion is positive and, therefore, is not compensated for. Thus, the resulting third-order dispersion coefficient for the stretcher–compressor system only rises, increasing the pulse picosecond pedestal. This problem can be solved in two ways. One is to change the dispersion properties of the compressor with allowance for the

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dispersion properties of a specific stretcher. To this end, a combination of two prisms and two diffraction gratings is used in the compressor scheme [12] or two grisms (a grism is a combination of an optical prism and a diffraction grating formed on one of its faces) is introduced into the compressor composition [13, 14]. Note that these compressor designs are difficult to align and lead to large losses in multipass schemes. Another way is to use stretchers based on fibre Bragg gratings, which make it possible to control the values and signs of higher order dispersions in wide limits, with a possibility of their adjustment to the parameters of a specific compressor in a fibre laser scheme [15]. However, these gratings can hardly be considered as generally available because of the complexity of their inscription.

Another, purely fibre solution is to apply special fibres with a complex refractive index profile, in which the wave and material dispersions are chosen so as to make the sum of higher order dispersions for the stretcher and compressor close to zero [16, 17]. In addition, the large second-order dispersion coefficient of this fibre stretcher allows one to stretch efficiently a pulse at a small fibre length, due to which the influence of nonlinear SPM effects in a fibre amplifier is weakened [18]. In this paper, we consider the possibility of using a heavily doped germanosilicate fibre with a W-profile refractive index and a core diameter of 2 μm to stretch femtosecond pulses for their subsequent amplification in an all-fibre amplifier up to energies of several microjoules at a wavelength of 1.03 μm.

2. Experiment and discussion of results

The experiments were performed using a femtosecond fibre laser system (see Fig. 1). The source of pulses (intended for subsequent amplification) was a femtosecond fibre master oscillator of laser pulses with a linear cavity scheme based on polarisation-maintaining fibres and intracavity compensation for the normal dispersion using a pair of diffraction gratings. The mode-locking regime was obtained using a semiconductor saturable absorber mirror, which was installed directly on one of the end faces of the linear fibre cavity. Pulsed radiation was extracted from the cavity through a fibre coupler. Because of the dispersion broadening in the fibre elements of the scheme, the pulses acquired a frequency modulation (chirp) and were stretched to 5 ps at the cavity output. Pulses could be compressed to 200 fs using an external compressor based on a pair of diffraction gratings. The pulse repetition rate of the master laser was 32 MHz at an average output power of 3 mW and the centre wavelength of 1030 nm. The optical spectrum and autocorrelation function of master laser pulses are shown in Fig. 2. The FWHM value for the autocorrelation function of a compressed pulse was (depending on the cavity tuning) 260 – 300 fs; therefore, with allowance for the value of deconvolution factor for a Gaussian pulse (1.42), the pulse width ranged from 183 to 211 fs.

Fibres of two types of the same length (50 m) were used as the stretcher material: single-mode polarisation-maintaining fibre PM980-XP6/125 (referred to as fibre PM6/125 below) and a single-mode fibre heavily doped with germanium oxide and having a W-profile refractive index and a core diameter of 2 μm (referred to as dispersion fibre DS2/125 below). The measured refractive index profile of DS2/125 fibre is shown in Fig. 3. The laser under study was completely implemented on a polarisation-maintaining fibre; however, in the case of the DS2/125 fibre, the polarisation direction in the A – B segment was set along the slow axis by fibre polariser P and polarisation controller PC. The loss in the DS2/125-based stretcher was mainly due to the difference in the core diameters for spliced PM6/125 and DS2/125 fibres. The loss was minimised using multiple welding with simultaneous monitoring of the transmitted radiation power. Radiation with an average

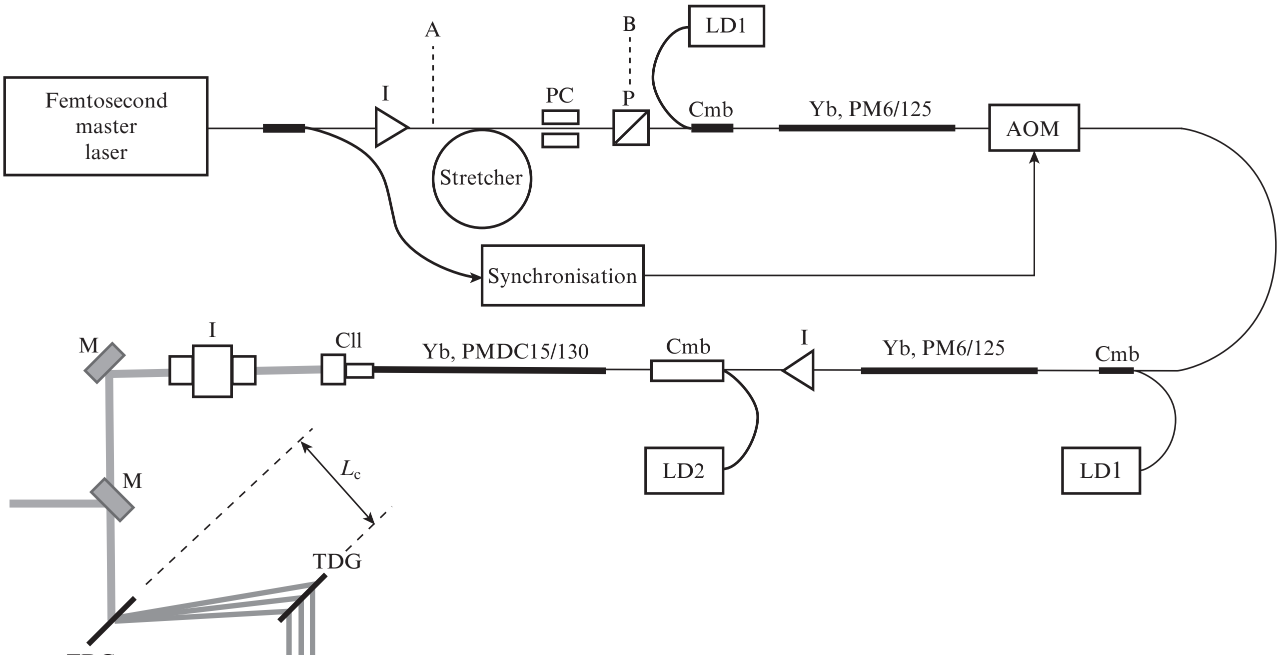

Figure 1. Schematic of a fibre laser: (I) isolator; (PC) polarisation controller; (P) polariser; (AOM) acousto-optic modulator; (Cll) collimator; (Cmb) combiner; (TDG) transparent diffraction grating; (L_c) intergrating distance in the compressor; (LD1) single-mode pump laser diode (200 mW, 976 nm); (LD2) multimode pump laser diode (20 W, 976 nm); (RRP) retroreflector prism; (M) highly reflecting mirror.

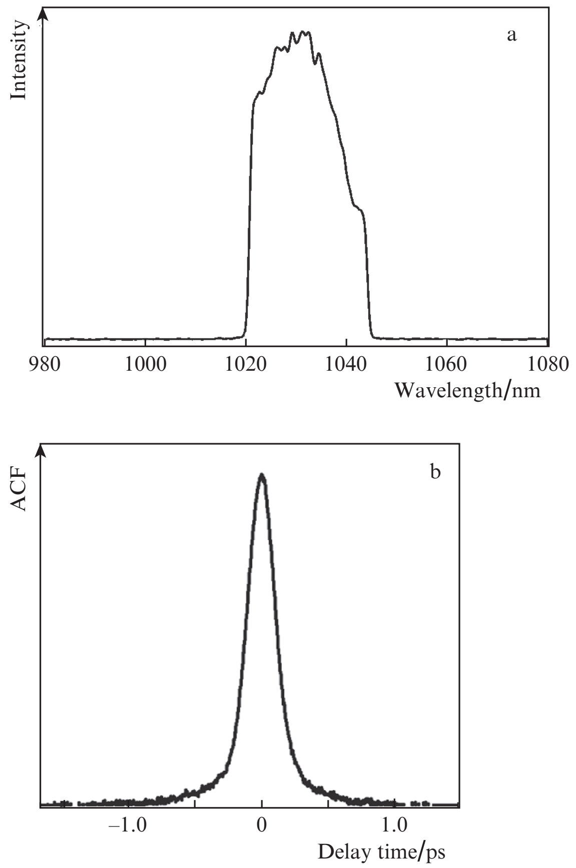

Figure 2. Output characteristics of femtosecond master laser: (a) optical spectrum and (b) pulse autocorrelation function after optimal compression, whose FWHM is 280 fs, a value corresponding to a pulse width of 200 fs.

power of about 1 mW arrived from the fibre stretcher to the input of the first preamplifier. The first preamplifier, based on a 1-m-long active fibre Nufem PM-YSF-HI 6/125, amplified the radiation power to 30–40 mW on average. Then the radiation arrived at the input of an acousto-optic modulator, which lowered the PRR to 1 MHz and reduced the average power to 1.2 mW.

The second preamplifier was designed according to the same scheme as the first one, and made it possible to vary the

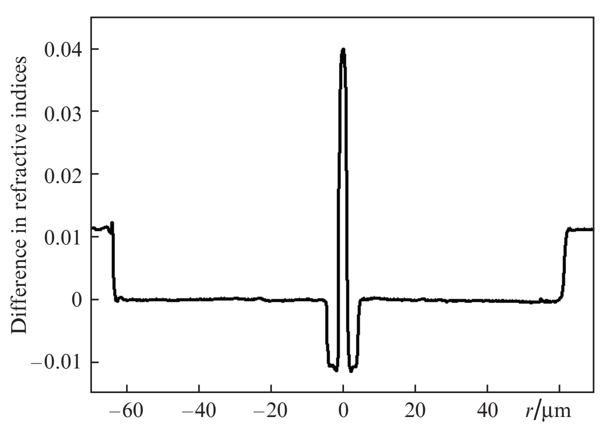

Figure 3. Refractive index radial profile, measured in the dispersion fibre DS2/125.

average radiation power from 2 to 20 mW at the input of power amplifier, where a 1-m segment of active fibre with a double cladding and a core diameter of 15 μm (Nufern PLMA-YDF-15/130-VIII) was applied. It was pumped by a multimode diode with an output average power up to 20 W at a wavelength of 976 nm. Pump radiation was introduced into the fibre through a combiner codirectionally with the signal radiation. The output amplified radiation from the active-fibre end face was collimated and directed into a compressor based on a pair of transparent diffraction gratings with a line density of 1600 mm^{-1}. The diffraction efficiency of each grating was 95%, which made it possible to provide a compressor transmittance of more than 80%. As a result of the amplification, the average power directly after the collimator reached 2.4 W, a value corresponding to a pulse energy of 2 μJ at the compressor output. The pulse width at the optimal intergrating distance L_c = 4.8 cm was 250 fs. The autocorrelation functions and optical spectra of the output pulse are shown in Figs 4 and 5 for two types of fibre stretchers. As follows from Fig. 4, using a stretcher based on the DS2/125 dispersion fibre, one can diminish significantly the lateral wings and picosecond pedestal of the output pulse. A replacement of the dispersion fibre with the conventional fibre PM6/125 in the stretcher leads to an essential spectral broadening and occurrence of additional spectral lines (Fig. 5).

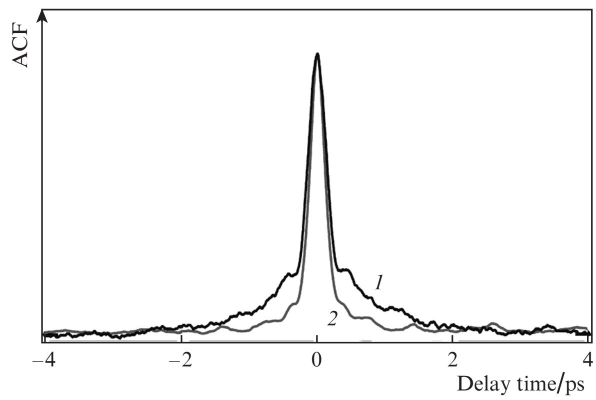

Figure 4. Autocorrelation function of the output pulse after compression using (*1*) dispersion fibre PM6/125 and (*2*) fibre DS2/125(2) in the stretcher. The fibre lengths are 50 m.

It is known that dispersion effects in a fibre are described by expanding the propagation constant $\beta = n(\omega)\omega/c$ in a Taylor series near the carrier frequency ω_0:

$$\beta(\omega) = \beta_0 + \beta_1(\omega - \omega_0) + \frac{1}{2}\beta_2(\omega - \omega_0)^2 + \frac{1}{6}\beta_3(\omega - \omega_0)^3 + ..., \quad (1)$$

where $\beta_m = (\mathrm{d}^m\beta/\mathrm{d}\omega^m)_{\omega=\omega_0}$ (m = 1, 2, 3, ...). There are some important relations linked with the dispersion coefficients β_m. The pulse envelope moves with a group velocity $v_g = 1/\beta_1$. The second-order coefficient β_2 determines the broadening of a pulse passing through the medium; it is related to the dispersion parameter D as follows:

$$D = \frac{\mathrm{d}\beta_1}{\mathrm{d}\lambda} = -\frac{2\pi c}{\lambda^2}\beta_2. \quad (2)$$

Figure 6 shows the spectral dependences of the dispersion parameters for the PM6/125 and DS2/125 fibres used in the

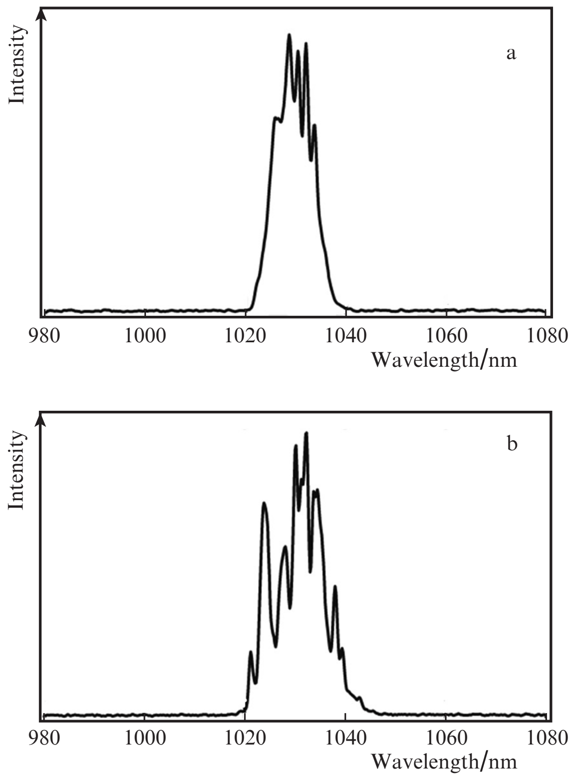

Figure 5. Output radiation spectra obtained using (a) dispersion fibre DS2/125 and (b) and fibre PM6/125 in the stretcher. The fibre lengths are 50 m.

experiments, as well as the calculated dependences $D(\lambda)$ for the DS1.5/125 and DS1.3/125 fibres, which have a core with a W-refractive index profile identical to that of the DS2/125 fibre but corresponding to core diameters of 1.5 and 1.3 μm, respectively.

Using the D values for each type of fibre at a wavelength of 1030 nm, one can easily estimate the pulse width after the stretcher from the formula

$$\tau_{str} \approx D\Delta\lambda L_{str}, \tag{3}$$

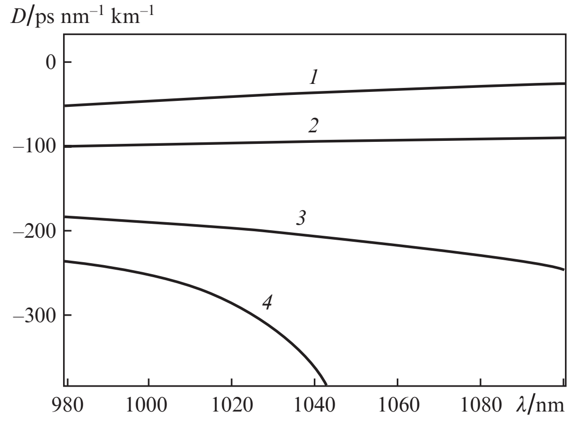

Figure 6. Dependences of the dispersion parameter D on the wavelength λ for (*1*) polarisation-maintaining fibre PM-980XP with a core diameter $d = 6$ μm and dispersion fibres (*2*) DS2/125 with $d = 2$ μm, (*3*) DS1.5/125 with $d = 1.5$ μm, and (*4*) DS1.3/125 with $d = 1.3$ μm.

where $\Delta\lambda$ is the spectral width at the output of femtosecond master laser, equal to 20 nm, and L_{str} is the fibre stretcher length (in km). Hence, we have τ_{str} = 40 ps or 90 ps for the pulse widths after the stretcher based on the PM6/125 or DS2/125 fibre, respectively. Thus, when a dispersion fibre is used, the pulse width increases by more than twice as compared with a conventional fibre of the same length. The increase in the pulse width before the power amplifier reduces the influence of SPM effects in the amplifying fibre. The SPM influence can quantitatively be determined by calculating the phase shift occurring when a pulse passes through the active medium [19]:

$$\phi_{SPM} = k_0 n_2 I L. \tag{4}$$

Here, $k_0 = 2\pi/\lambda$; n_2 is the nonlinear refractive index; I is the peak intensity; and L is the interaction length. Using (4), one obtains phase shifts of 9π and 4π for 40- and 90-ps pulses, respectively, on a 1-m-long active fibre in the power amplifier. The ϕ_{SPM}/π value corresponds approximately to the number of oscillations (9 and 5) in the spectra broadened due to the SPM (see Fig. 4) for, respectively, the PM6/125 and DS2/125 fibres used in the stretcher.

Using a stretcher based on a dispersion fibre, one can not only significantly reduce the SPM influence but also partially compensate for the influence of the third-order dispersion in the stretcher–compressor complex. Since the third-order dispersion coefficient β_3 is positive for the PM6/125 fibre at λ = 1030 nm, the total value of β_3 in the stretcher–compressor system only increases. The coefficient β_3 is negative for the dispersion fibre DS2/125 at λ = 1030 nm; correspondingly, it partially compensates for the positive third-order dispersion of the compressor.

To confirm that the DS2/125 fibre improves significantly the dispersion matching in the stretcher–compressor system, we considered two stretchers having the same output-pulse width in order to provide an identical SPM effect on pulses. The first and second stretchers contained, respectively, a 120-m conventional fibre PM6/125 and a 50-m dispersion fibre DS2/125. The width of the pulses broadened by the stretchers of both types was 90 ps. However, the pulse at the output of the stretcher based on the conventional fibre PM6/125 was compressed to only 500 fs, whereas the stretcher with the dispersion fibre DS2/125 made it possible to compress the pulse to 250 fs. This fact is indicative of specifically dispersion mismatch in the stretcher (PM6/125)–compressor system. The possibility of compensating for the third-order dispersion of the compressor using a fibre stretcher can be considered using Table 1, which contains the dispersion coefficients separately for the stretcher and compressor, as well as the total values of dispersion coefficients characterising the stretcher–compressor system for a pulse broadened in a fibre stretcher to 90 ps.

The ratio $K_{cpr} = \beta_3^{cpr}/\beta_2^{cpr}$ for a compressor based on diffraction gratings with a line density of 1600 mm^{-1} is independent of the intergrating distance and amounts to 8.6 fs at a wavelength of 1030 nm. The K_{cpr} value may decrease to 7 fs with an increase in the angle of beam incidence on a grating by 4° (counting from the optimal angle of 55.5° for a 1600 mm^{-1} grating). The ratio $K_{str} = \beta_3^{str}/\beta_2^{str}$ for the stretcher is independent of the fibre length. In the case of optimal compression, the following equality holds true: $\beta_2^{str} = -\beta_2^{cpr}$; therefore, the ratio of the third-order dispersion coefficients $K_{str}/K_{cpr} = \beta_3^{str}/\beta_3^{cpr}$ determines the possibility of compensat-

Table 1. Second- and third-order dispersion coefficients for the stretcher–compressor system operating at λ = 1030 nm for stretchers based on fibres of four types.

Element	$\beta_2/10^{-6}$ fs^2	$\beta_3/10^{-7}$ fs^3
Compressor	–2.7	2.3
PM6/125, L_{str} = 120 m	2.7	0.5
PM6/125 + Compressor	0	2.8
DS 2/125, L_{str} = 50 m	2.7	–0.15
DS 2/125 + Compressor	0	2.15
DS 1.5/125, L_{str} = 28 m	2.7	–0.5
DS 1.5/125 + Compressor	0	1.8
DS 1.3/125, L_{str} = 15 m	2.7	–2.1
DS 1.3/125 + Compressor	0	0.2

Note. The stretcher length L_{str} corresponds in each case to the same second-order dispersion β_2 and broadened-pulse width of 90 ps. A compressor with gratings characterised by a line density of 1600 mm^{-1} and intergrating distance L_c = 4.8 cm was used in all versions.

ing for the third-order dispersion in the stretcher–compressor system at a given wavelength. For the DS 2/125 fibre, the K_{str} value is only –0.5 fs at λ = 1030 nm, which provides compensation at a level of several percent. Using fibres with a smaller core diameter in the stretcher, one can compensate for the third-order dispersion to a higher degree. For example, for the DS1.5/125 and DS1.3/125 fibres, the K_{str} values are –1.9 and –7.8 fs, which provide compensation at levels of 22% and 91%, respectively. Using the DS1.3/125 fibre, one can easily obtain 100% compensation of the third-order dispersion either applying small adjustment of the tilt angle of compressor gratings or passing to a generation wavelength of 1035 nm.

3. Conclusions

The application of heavily doped germanosilicate fibres with a small core diameter as stretchers of ultrashort pulses in fibre lasers with a diffraction-grating-based output compressor was investigated. It was shown that these fibres provide dispersion matching in the stretcher–compressor system and reduce the SPM influence in the amplifying fibre due to the significant pulse elongation in the stretcher. As a result, the output pulse shape is improved, and the number of oscillations in the output spectrum decreases. The negative third-order dispersion in germanosilicate fibres with a small core diameter makes it possible to compensate for the positive third-order dispersion of the compressor. A calculation of the dispersion parameters showed that the degree of compensation increases with a decrease in the core diameter in a germanosilicate dispersion fibre and reaches 100% for a fibre having a core diameter of 1.3 μm.

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