Mode-locked Thulium-Doped Fiber Lasers based on Highly Ge-doped Fibers

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1 RESEARCH PROBLEM

Thulium-doped ultrashort pulsed fiber lasers (TDFs) attract increased attention due to their broad gain spectrum extending from 1.8 to 2.1 µm (Hanna, 1990; Barnes, 1990), possibility to produce high power and highly efficient tunable femtosecond pulses (Wu, 2007; Jackson, 2007; Sorokina, 2014) in the very interesting for many practical applications wavelength range around 2 µm (Dvoyrin, 2014; Sorokina, 2014), including eye-safe LIDAR, medicine, high resolution spectroscopy and remote sensing (Sorokina, 2014).

In the wavelength region of 2 µm silica-based fibers typically exhibit anomalous group delay dispersion (GDD). Therefore, without dispersion compensation TDF lasers are restricted to soliton operation, which has been demonstrated with different mode-locking schemes (Nelson, 1995; Sharp, 1996; Solodyankin, 2008). Alternatively, elements for dispersion compensation can be implemented in the cavity, enabling the laser to operate in the stretched-pulse regime. This regime is characterized by breathing dynamics that reduces the total nonlinear phase shift and allows for relatively high pulse energies compared to the fundamental soliton regime, while the pulses can still be compressed to very short durations outside the resonator (Nelson, 1997).

Anomalous dispersion regime in the simple dispersion uncompensated fiber laser leads to the typical limitation of both pulse energy and duration to picojoules and picoseconds, respectively. However, implementation of dispersion compensation usually requires additional components, specialty fibers, i.e., holey fibers, or even bulk elements. This technique leads to the complexity of the scheme and decreases its reliability. Such specialty fibers often have fragile or mechanical splices with conventional silica-based fibers; the insertion of bulk elements substantially decreases the laser performance. The Ge-doped Tm-codoped silica-based fibers with anomalous dispersion have already shown to be effective as a laser material (Rudy, 2012). The possibility of high doping of such fibers with Tm allows improving the quantum efficiency (Rudy, 2012) and decreasing the length of the active fiber. Highly Ge-doped silica-based fibers exhibit normal dispersion in the 2 µm wavelength region. Such fibers naturally allow constructing an all-fiber laser with normal cavity dispersion. Excellent mechanical properties and close relation to the conventional silica-based fibers allow good reliable solid splices of the highly germanium-doped fibers with the conventional ones. The final construction is simpler and allows producing femtosecond pulses as it will be revealed in what follows. This makes such fibers promising for producing of particularly short, power scalable mode-locked pulses. The first works, on producing stable continuous-wave lasing were reported in (Dvoyrin, 2011; Dvoyrin, 2010).

2 OUTLINE OF OBJECTIVES

In this work, we present our first results and the perspectives of the development of the Tm-doped fiber laser based on active fibers of normal dispersion. We propose the first femtosecond SESAM mode-locked all-fiber laser based on the highly Ge-doped thulium-doped normal dispersion active fiber. In this article we focus our attention on three particular configurations: laser operating in the anomalous cavity dispersion regime, laser operating in the regime of nearly zero cavity dispersion and laser operating in the normal cavity dispersion regime without the use of the additional dispersion compensating elements. The pulses were amplified by a compact TDF MOPA laser system.

For the nearly zero and normal cavity dispersion regimes the femtosecond pulses with several nanojoule energy were obtained at the wavelength of around 1.88 nm. The pulses were compressed down to 800 fs using a simple fiber compressor represented by a piece of a conventional fiber.

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3 STATE OF THE ART

There are several demonstrations of passively mode-locked TDF lasers, using various mechanisms of mode-locking. These demonstrations include nonlinear polarization rotation (NPR) (Sharp, 1996; Wang, 2010), semiconductor saturable absorber mirrors (SESAM) (Sharp, 1996), carbon nanotube based saturable absorbers (Solodyankin, 2008; Kieu, 2009) and graphene based saturable absorber (Zhang, 2012). For instance, Nelson et al. demonstrated NPR-based mode-locked thulium fiber laser with 500 fs pulses generation (Nelson, 1995). In another work, Sharp et al. used a semiconductor SESAM in a TDF laser to achieve 190 fs pulses (Sharp, 1996). More recently, Engelbrecht et al. reported a laser with grating-based dispersion compensation and double-clad TDF. The laser operated in the stretched pulse regime (Engelbrecht, 2008) with pulse energy as high as 4.3 nJ and de-chirped pulse duration around 300 fs. Mode-locked operation of dispersion-compensated TDF lasers has also been successfully demonstrated (Solodyankin, 2008; Haxsen, 2008).

4 METHODOLOGY

A mode-locked TDF laser has been built using the all-fiber linear cavity configuration. The TDF was produced by the modified chemical vapor deposition method. It had 55% mol.% concentration of GeO_2 in the core (Dvoyrin, 2011; Dvoyrin, 2010; Dvoyrin, 2011). The schematic of the laser and the amplifier are shown in Fig.1.

The cavity was formed with a SESAM saturable absorber, a fiber coupler used for launching pump radiation into the cavity, a piece of 3 m length of the TDF with a highly Ge-doped core of 3μm diameter and NA of 0.49, a fiber loop mirror with the output coupling of 5%, and a piece of the conventional telecommunication fiber (SMF-28). Excellent mechanical properties and close relation to the conventional silica-based fibers allow good reliable solid splices of the TDF with the conventional ones. The measured splice loses were found to be 1.5 dB per splice. The length of the SMF-28 fiber was varied in order to investigate the laser performance in the wide range of the cavity dispersion. It is worth noting that all the components used in the fiber laser had fiber outputs based on the SMF-28 fiber.

The amplifier was based on a piece of 14 m length of the same TDF. The laser was pumped by one or two laser diodes (Princeton Lightwave Inc.) operating at the wavelength of 1550 nm and 1630 nm, depending on the configuration, while for the pumping of the amplifier we used an Er-doped fiber laser operating at the wavelength of 1.61 μm (IPG Photonics Inc.)

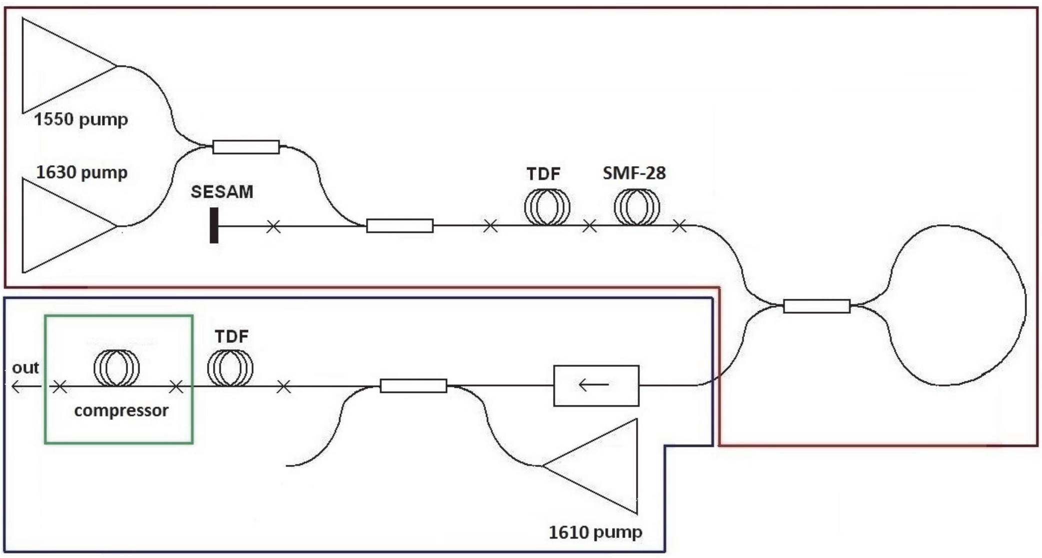

Figure 1: The schematic of the TDF laser (red frame) and amplifier (blue frame).

5 STAGE OF THE RESEARCH

5.1 Experimental Results

5.1.1 Anomalous and Nearly Zero Cavity Dispersion Regimes

The maximum output average power for both anomalous dispersion configurations of the laser oscillator was 1.9 mW with 0.7% slope efficiency. The laser emission wavelength was centered around 1.88 μm. The dispersion of the fibers is of 35±1 and -15±1 ps/nm*km for the SMS-28 fiber and for the TDF, respectively, at the laser emission wavelength (Klimentov, 2012). In our experiments the cavity dispersion varied in the range of 0.002-0.404 ps/nm when changing the SMF-28 fiber length from 1.35 to 12.8 m. For our particular configurations: laser operating in the anomalous cavity dispersion regime and laser operating in the regime of nearly zero cavity dispersion, the cavity dispersion was 0.148±0.005 and 0.002±0.001 ps/nm, respectively. The corresponding pulse energies inside the laser cavity were found to be 1.6 and 3.2 nJ. These energy values noticeably exceed the values obtained in frames of the soliton theory, which can be estimated as 0.11 and 2.45 nJ, but may be explained by the stretched-pulse or "dispersion management" regime (Tamura, 1995; Tamura, 1993), where the pulses travel through the fiber spans of alternating dispersion and experience stretching and recompression in every resonator round trip. As the average pulse duration in the resonator can be increased, the pulse energy can be increased accordingly.

After amplification of the pulses we achieved the average output power of 86 mW at the repetition rate of 12 MHz corresponding to the pulse energy of 7.3 nJ and 3.7 nJ for the longer and shorter cavity, respectively, with the amplifier slope efficiency of 3.8%.

The spectrum and autocorrelation trace for the cavity dispersion of 0.148±0.005 ps/nm are shown in Fig. 2(a), indicating 1.68-ps pulses with the spectral full width at half maximum (FWHM) of 2.7 nm. The length of SMF-28 fiber was 5.5 m and the length of TDF was 3 m. The time-bandwidth product was 0.43 indicating that the pulses were not transform-limited. In that regime the laser was self-starting and the central wavelength was 1879 nm. With the cavity dispersion decrease the mode-locking threshold decreased slightly (from 155 to 145 mW of the pump power); however, the maximum output power of the laser and the amplifier remained at the same level as previously, while the emission spectrum was broadened from 2.7 to 5.2 nm and the pulse duration reduced from 1.68 ps to 900 fs.

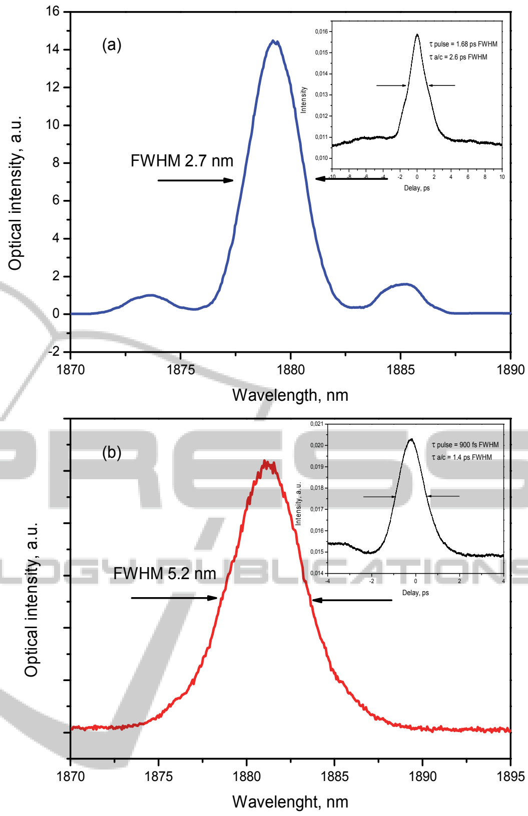

Figure 2: Spectra and autocorrelations for the mode-locked TDF laser operating in anomalous dispersion regime (a), and the mode-locked TDF laser with the nearly zero cavity dispersion (b).

The spectrum and autocorrelation trace for the nearly zero cavity dispersion of 0.002±0.001 ps/nm are shown in Fig. 2(b), indicating 900-fs pulses with the FWHM of 5.2 nm and the repetition rate of 23.5 MHz. In that configuration the laser produced transform-limited pulses with the sech^2 pulse shape and the time-bandwidth product of 0.315. For this configuration the length of SMF-28 fiber was 1.35 m and the length of the TDF fiber was 3 m.

The key feature of this work is the use of the highly Ge-doped active fiber with normal dispersion at 2 μm. Passive highly Ge-doped fibers can be used for dispersion compensation of the conventional silica-based fibers known to have high anomalous dispersion in the 2 μm spectral region. Same fibers doped with thulium can significantly reduce the complexity of a laser scheme allowing achieving the zero cavity dispersion or even normal dispersion without the use of separate pieces of an active fiber and a dispersion compensation fiber.

5.1.2 Normal Cavity Dispersion Regime

It is known that the highest pulse energies can be obtained in the normal cavity dispersion regime. So, we have modified the laser cavity by changing its length thus changing the cavity dispersion from anomalous to normal and studied the performance of the laser.

All the SMF-28 fiber pieces were removed from the cavity, except the short fiber ends of the couplers and the fiber loop mirror. In this configuration the rest of SMF-28 fiber length was 68 cm resulting in the total cavity dispersion of -0.02±0.001 ps/nm. The mode-locking threshold in the normal cavity dispersion regime decreased to 90 from 145 mW. The laser remained self-starting. The emission central wavelength was slightly blue-shifted to 1868 nm due to change of the SESAM mirror position during reconfiguration of the laser.

The radio frequency (RF) spectrum measured with 200 kHz frequency span and 1 kHz resolution bandwidth is shown in Fig. 3 (upper). The repetition rate of the laser was 26.78 MHz. A graph at the Fig. 3 (lower) illustrates the RF spectrum recorded in the 200 MHz frequency span and 100 kHz resolution bandwidth, showing a broad spectrum of harmonics. No signs of dual-pulsing have been observed.

Since the intracavity pulse energy was not limited in this regime by the fundamental soliton energy, we increased the pump power of the laser by adding the second pump diode. The average maximum output power of the laser reached 2.3 mW

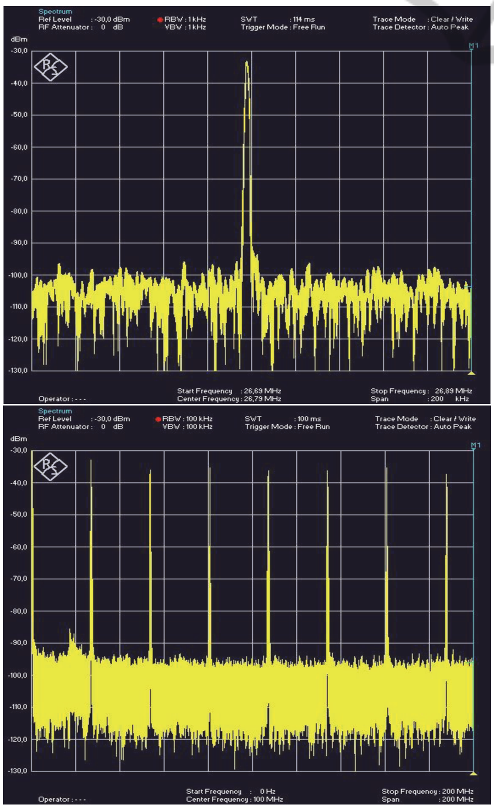

Figure 3: Measured RF spectrum of mode-locked output: with a 200 kHz frequency span and 1 kHz resolution bandwidth (upper); with a 200 MHz frequency span and 100 kHz resolution bandwidth, showing a broad spectrum of harmonics (lower).

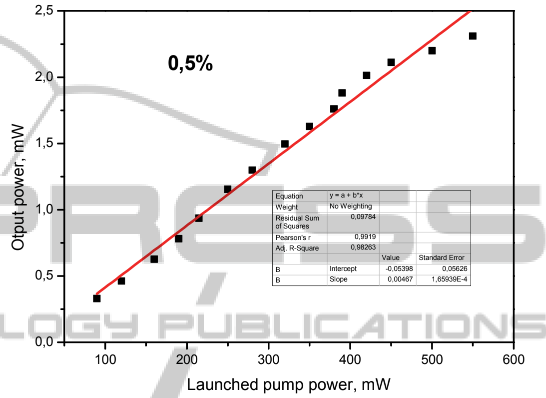

Figure 4: The laser slope efficiency.

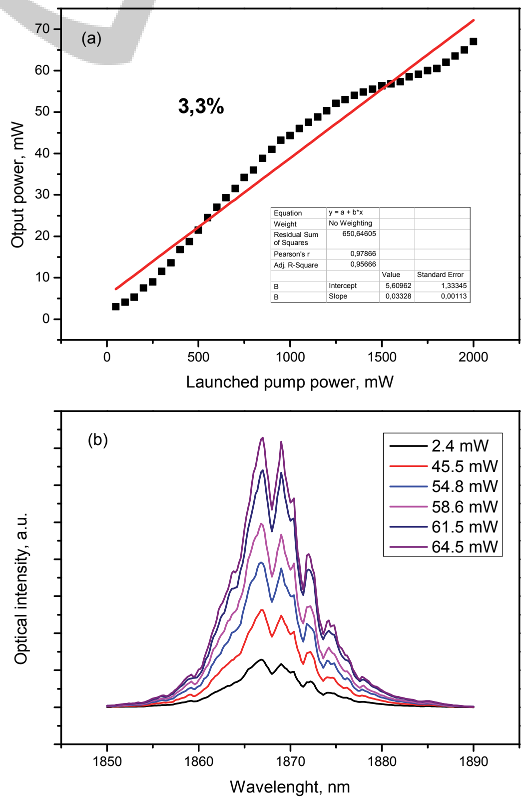

Figure 5: The amplifier slope efficiency (a) and the evolution of the spectrum after amplification (b).

and was limited by the available pump only. The laser slope efficiency is shown in Fig. 4.

After the amplification of the pulses with the same amplifier we achieved the average maximum output power of 70 mW with the repetition rate of 26.8 MHz corresponding to the pulse energy of 2.6 nJ with the amplifier slope efficiency of 3.3%. The amplifier slope efficiency and the evolution of the spectrum after amplifier are shown in Fig. 5. As it can be seen, the amplification did not change the shape of the spectrum.

The spectrum and autocorrelation trace for the laser operating in normal dispersion regime with the cavity dispersion of -0.02±0.001 ps/nm are shown in Fig. 6, indicating 1.35-ps pulses with the spectral FWHM of 9 nm.

It is worth noting that the launched pump power exceeded the specification limit of the input coupler of the amplifier. To avoid damage we placed it in a water tank to allow a better heat dissipation. We believe that the visible bending of the amplifier efficiency curve is caused by the thermal effects inside the coupler.

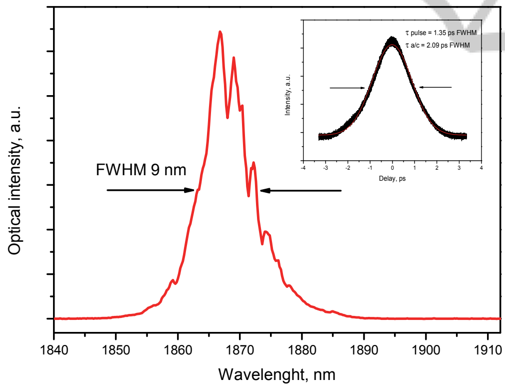

Figure 6: Spectrum and autocorrelation for the mode-locked Tm-doped laser operating in normal dispersion regime.

5.1.3 Pulse Compression

The pulses of the TDF laser operating in normal dispersion regime after amplification were compressed using the fiber compressor, Fig. 1. The compressor was formed by the SMF-28 fiber. The optimal length of fiber for the efficient compression was found to be 3.2 m. It was found, that elongation of this length by several meters weakly affected the pulse duration. The Fig. 7 shows the autocorrelations of the mode-locked pulses before the compression, and after the compression with two lengths of the SMF-28 fiber of 3.2 and 8 m. With the compressor of the optimal length the initial pulses were compressed from 1.35 ps down to 800 fs and the spectrum was broadened from 9 to 10 nm FWHM. The increase of the compressor length in 3 times, approximately, did not lead to the sufficient change in the pulse duration; the pulses from the 8 m compressor were only slightly longer.

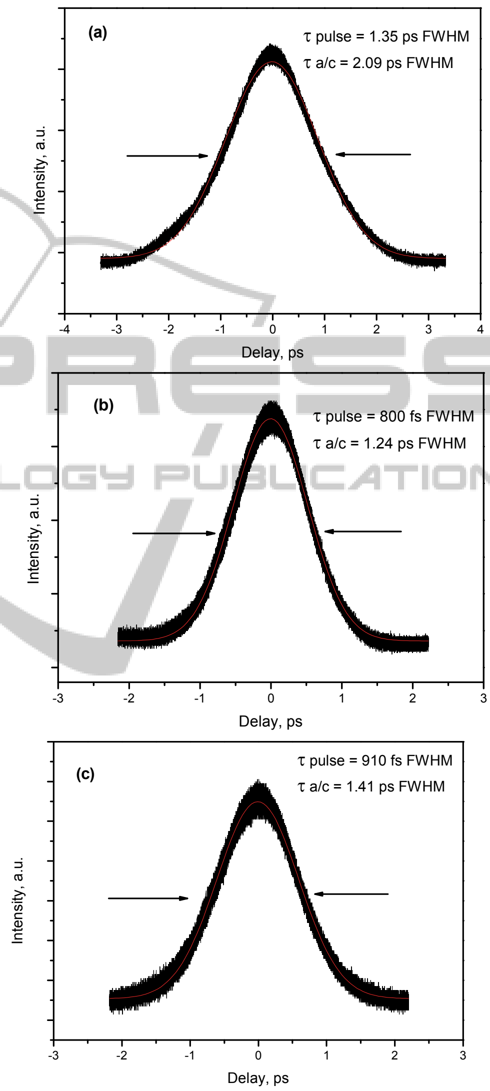

Figure 7: The autocorrelations of the mode-locked pulses from the Tm fiber laser operating in normal dispersion regime: before the compression (a), the autocorrelation measured after the compression by 3.2 m compressor (b), and the compression by the SMF-28 with the length 8 m (c).

5.2 Discussion

As compared to the conventional approach, we suggest a simpler scheme with a higher reliability. No additional dispersion-compensation, e.g. any fibers or bulk elements, was used in our laser. However, it operated in the normal dispersion regime. It is worth to note, that the operation near zero cavity dispersion allowed us to produce femtosecond pulses directly from the oscillator in contrast to the picosecond laser with essential anomalous dispersion. Variation of remaining length of the pieces of the input/output conventional anomalous dispersion fibers from the components used in the laser naturally allowed us to carry out a simple form of the dispersion management resulted, however, in femtosecond pulse generation. The compression of the pulse from the normal-dispersion laser was naturally provided by the laser output piece of the conventional fiber and allowed us to achieve the shortest, 800 fs pulses. At the same time the pulses energy was as high as 2.6 nJ. The whole system exhibited a much simpler level of complexity than the conventional fiber lasers with dispersion compensation. This is a noticeable improvement of the mode-locked fiber laser construction.

Excellent mechanical properties and close relation to the conventional silica-based fibers allow good reliable solid splices of the highly germanium-doped fibers with the conventional ones. The measured splice losses were found to be 1.5 dB per splice. It is worth noting that a standard fusion splicer program was used. The splice loss can be reduced in future by modification of the electrical fusion splicer program or use of fibers with similar mode diameters.

5.3 Conclusion

We have demonstrated the first femtosecond SESAM mode-locked TDF laser based on the active fiber with highly Ge-doped core with the normal dispersion in the spectral region near 2 µm. The change of the length of the conventional telecommunication fiber inside the laser cavity allowed variation of the total cavity dispersion in the range of -0.02-0.404 ps/nm. The stable laser operation was obtained in three different dispersion regimes: laser operating in the anomalous cavity dispersion regime, laser operating in the regime of nearly zero cavity dispersion, and laser operating in the normal cavity dispersion regime. The lasers operated at the wavelength of ~1.88 µm. The pulses from the master oscillator were amplified in the core-pumped TDF amplifier based on the same active fiber as the laser.

The amplification resulted in the output power of 86 mW corresponding to the pulse energy of 7.3 and 3.7 nJ for the laser cavity dispersion of 0.148 and 0.002 ps/nm, respectively. In the case corresponding to the nearly zero cavity dispersion, the laser produced transform-limited soliton pulses with the time-bandwidth product of 0.315 and the pulse duration of 900 fs, with the spectral FWHM of 5.2 nm.

For the laser operating in the normal cavity dispersion regime the amplification resulted in the output power of 70 mW corresponding to the pulse energy of 2.6 nJ. The laser produced pulses with the pulse duration of 1.35 ps, with the FWHM of 9 nm.

Finally, we could compress the pulses down to 800 fs by using the all-fiber compressor, based on the SMF-28 fiber.

6 EXPECTED OUTCOME

The laser output power is limited by the available pump power only; we predict, based on our calculations, that further optimization resulting in the efficiency increase will allow us to demonstrate more than an order of magnitude higher pulse energies, as there is no fundamental limitations for the pulse energy in the normal-dispersion laser except for the thermal load and the material damage threshold.

Evidently, all the regimes can be improved by the reducing of the splice losses, by the use of the highly Ge-doped active fibers with higher concentration of Tm, and, for the normal dispersion cavity regime, by applying higher pump power, which is planned for the near future experiments. Nevertheless, the present results already demonstrate the high potential of such fibers for producing of ultra-short femtosecond nanojoule pulses in the vicinity of 2 µm directly from a SESAM mode-locked fiber oscillator.

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The expected outcome of my research is the reliable stable ultra-short pulsed all-fiber MOPA system operating in the 2 µm wavelength region, as well as the power scaling of this MOPA up to 10 W output power by adding the second fiber amplifier stage; design and demonstration of a fiber based supercontinuum source and tests of the developed laser sources for practical applications, e.g. medicine, high resolution spectroscopy and remote sensing.

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