Switchable dual-pulse-shape mode-locked figure-eight all-PM fibre master oscillator with 0.5 W-level average output

Sergey Kobtsev[a,b], Aleksey Ivanenko*[a], Yuri Fedotov[a,b],
Sergey Smirnov[a], Artur Golubtsov[a], and Sergey Khripunov[a]
[a]Division of Laser Physics and Innovative Technologies, Novosibirsk State University, Pirogova 2, Novosibirsk, 630090, Russia;
[b]"Tekhnoscan - Lab" LLC, Inzhenernaya 26, Novosibirsk, 630090, Russia

ABSTRACT

For the first time a method for switching between generation of single- and double-scale pulses has been demonstrated in a mode-locked figure-eight NALM-based all-PM-fibre Yb master oscillator by adjustment of two pumps power. Introduction into a F8 configuration of a non-linear amplifying loop mirror with two active media not only ensured relatively high average output power of the master oscillator (> 0.5 W at 22-MHz repetition rate), but also allowed switching laser operation from one pulse type (single-scale with duration of < 10 ps) to another - femtosecond clusters with envelope width of 16 ps and sub-pulse duration < 200 fs.

Keywords: mode-locked laser, fibre laser, figure-eight fibre laser, ultrafast laser, nonlinear amplifying loop mirror

1. INTRODUCTION

Mode-locked fibre lasers[1] became essential and widely used sources of short light pulses due to the inherent advantages of fibre lasers: relatively high generation efficiency, compact dimensions, maintenance-free operation (no optical surfaces to clean or align, &c), and long service time. One of the simplest methods of mode locking in fibre lasers relies on Kerr non-linearity of the optical fibre material itself. It is analogous to the way solid-state lasers use Kerr lensing, although in fibre lasers, a different aspect of Kerr non-linearity is used, which manifests itself as non-linear polarisation evolution (NPE)[2]. NPE mode-locked fibre lasers boast a uniquely wide range of output radiation parameters[3-5]. Duration of pulses generated in such lasers may vary from tens and hundreds of femtoseconds[6-11] to several nanoseconds[12-17]. Modification of the cavity length of an NPE mode-locked fibre laser allows corresponding adjustment of the pulse repetition rate from hundreds of MHz to tens kHz[14,18], as well as scaling of the output pulse energy in the range from the nanojoule to microjoule level[6-9,13,18]. Mode-locked fibre lasers with total positive intra-cavity dispersion[19,20] are especially interesting because they can generate pulses with higher average power[13,14] and energy[14,18]. Besides, the presence of a significant chirp in such pulses makes it possible to use chirped-pulse amplification without prior pulse stretching.

It is pertinent to note that NPE-based fibre lasers exhibit not only a widest range of radiation parameters, but also various types of laser operation[5,21], including generation of double-scale optical lumps with picosecond envelope and femtosecond noise-like oscillations[22–25]. It is remarkable that multiple types of laser generation may be realised in a single laser device at different non-linear evolution of the radiation polarisation, which is determined by the pump radiation power and the specific settings of the intra-cavity polarisation controllers. Earlier, it was demonstrated that generation of single-scale optical pulses and double-scale optical lumps may be achieved at will both in one single resonator of an NPE mode-locked fibre laser[26] and in a single figure-of-eight (F8) fibre laser with non-linear amplifying loop mirror[27].

While the importance of single-scale optical pulses for applications is self-evident, the practical prospects of double-scale optical lumps until very recently remained uncertain. However, as it was shown[28,29], non-linear transformation of double-scale optical lumps may be more efficient in comparison to single-scale optical pulses, thus suggesting possible practical opportunities.

*ivanenko.aleksey@gmail.com; phone/fax +7 383 363 4165; www.nsu.ru/srd/lls/english/index.htm

Fiber Lasers XIII: Technology, Systems, and Applications, edited by John Ballato, Proc. of SPIE
Vol. 9728, 97281M · © 2015 SPIE · CCC code: 0277-786X/15/$18 · doi: 10.1117/12.2211462

Downloaded From: http://proceedings.spiedigitallibrary.org/ on 03/13/2016 Terms of Use: http://spiedigitallibrary.org/ss/TermsOfUse.aspx

Additionally, double-scale optical lumps are densely filled with femtosecond noise-like oscillations, making them equivalent to femtosecond pulses with ultra-high repetition frequency. This may be useful in material processing applications. Therefore, fibre lasers capable of alternatively generating single-scale optical pulses and double-scale optical lumps offer a better functionality that makes them more attractive. Implementation of such lasers on the basis of NPE mode locking is not optimal because the cavity birefringence in these lasers is subject to environmental drift, for example because of changes in the ambient temperature of due to creep in fibre polarisation controller setting (these controllers rely on compression or torsion of amorphous optical fibre).

F8 fibre lasers mode-locked by non-linear amplifying loop mirrors (NALM)[30] constitute an attractive alternative to NPE mode-locked fibre lasers, since F8 fibre lasers do not contain any parameter, whose value could drift significantly due to fundamental peculiarities of the cavity design or the nature of the mode locking method. Aside from this, NALM-mode-locked F8 fibre lasers are able to provide relatively high average and peak powers of the output radiation[31].

The objective of the present work was to demonstrate generation of single-scale optical pulses and double-scale optical lumps in a NALM-mode-locked F8 fibre laser not by mechanically setting polarisation controllers, as it was done[27], but instead via electronic control over the power of two radiation sources pumping two different active media in the NALM.

2. EXPERIMENTAL SETUP

The experimental set-up is schematically presented in Fig. 1. The laser's F8 cavity consisted of two coupled loops, one of which was active and the other one, passive.

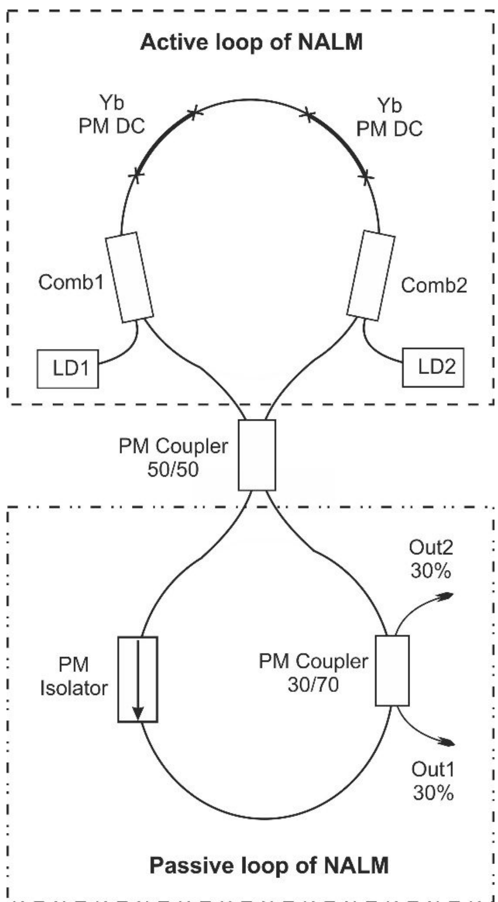


Figure 1. Experimental configuration.

Downloaded From: http://proceedings.spiedigitallibrary.org/ on 03/13/2016 Terms of Use: http://spiedigitallibrary.org/ss/TermsOfUse.aspx

Both the active and the passive cavity loops were made of polarisation-maintaining fibre and they were connected through a 2x2 polarisation-maintaining fibre-optical coupler. The F8 fibre laser cavity was composed of elements capable of withstanding average powers exceeding 2 W.

The cavity active loop formed a NALM and consisted of two stretches of active fibre and two combiners needed for coupling in the pump radiation. In the active part, two pieces (2 and 3 m long) of double-clad ytterbium-doped fibre were used with absorption of 3.9 dB/m at 978 nm. The presence of two separate active media within the NALM permitted control of the active loop non-linearity (by adjustment of the relative gain in the two active fibres determined by the values of the two pump sources) and the non-linear phase incursion of the two waves counter-propagating in the active loop.

The active fibres were pumped with two corresponding multi-mode laser diodes emitting at 978 nm through fibre-optical combiners. The top output power of each laser diode was 5.5 W.

The passive cavity loop was composed of a polarisation-maintaining (PM) optical Faraday isolator used to select the direction of travel along the passive loop and a PM coupler with coupling ratio 30 / 70 (in order to guide the radiation out of the resonator).

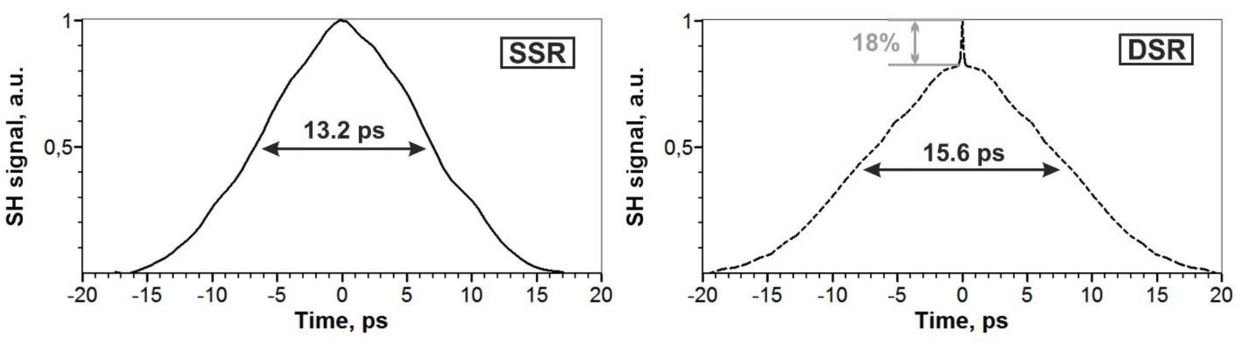
3. RESULTS

Mode-locked operation was triggered when the total power of the two pump sources exceeded 4 W. Adjustment of the ratio of the two powers allowed us to achieve various mode-locked generation regimes.

The two most typically observed pulsed regimes were as follows. The first pulsed regime hereafter referred to as SSR (Single-Scale Regime) generated single-scale optical pulses. The second regime that we will call DSR (Double-Scale Regime) was characterised by generation of double-scale optical lumps. SSR is observed at the pump power values Pump1 = 2.57 W and Pump2 = 2.17 W, whereas DSR is triggered at Pump1 = 2.86 W and Pump2 = 2.77 W.

The two above regimes could be switched from one to the other by adjustment of the pump laser diode output. In order to obtain the chosen regime (SSR or DSR), it was necessary to set the above-mentioned levels of pumping radiation Pump1 and Pump2 and, as soon as they were reached, the corresponding regime was triggered automatically.

Figure 2 shows the auto-correlation functions (ACF) corresponding to the two identified generation regimes. In SSR, the width of the pulse ACF amounted to 13.2 ps. In comparison, DSR produced a double-scale ACF with a narrow central peak of less than 200 fs sitting on top of a 15.6-ps pedestal.

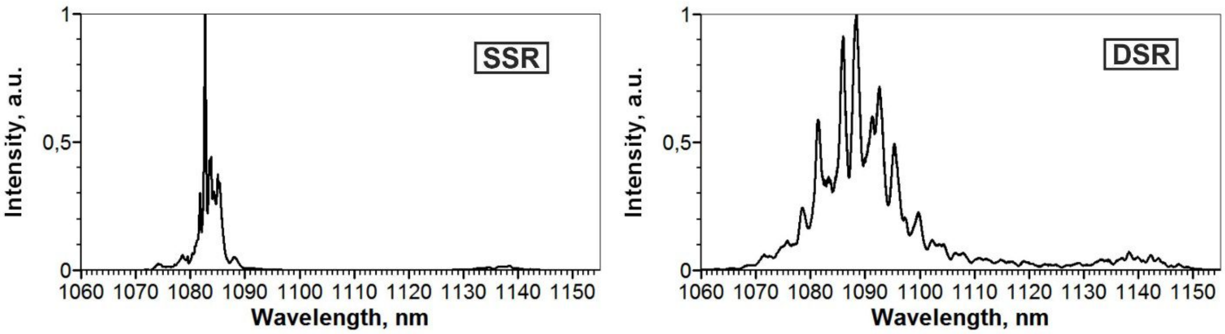


a) b)

Fig. 2. Auto-correlation functions of two typical generation regimes. a) SSR (generation of single-scale optical pulses) and b) DSR (generation of double-scale optical lumps).

The output radiation spectra corresponding to the two typical generation regimes are given in Fig. 3. In SSR, the spectrum width was 3 nm, whereas in DSR, a broader spectrum was observed with approximately 12-nm width.

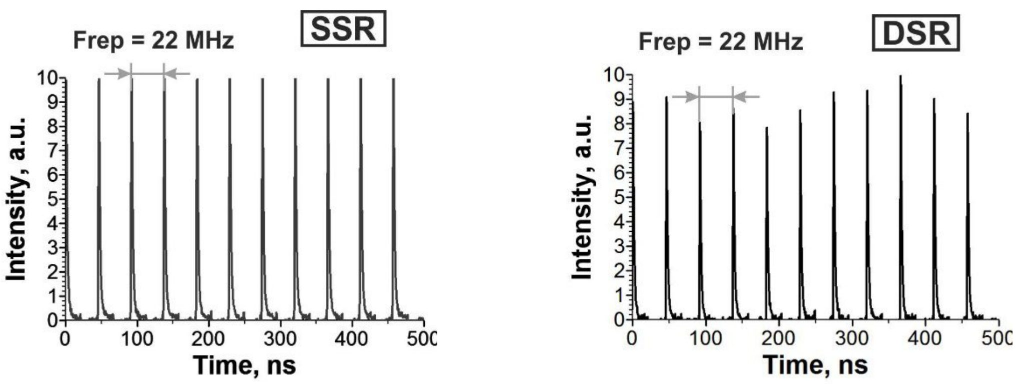
Downloaded From: http://proceedings.spiedigitallibrary.org/ on 03/13/2016 Terms of Use: http://spiedigitallibrary.org/ss/TermsOfUse.aspx



a) b)

Fig.3. Optical spectrum: a) SSR (generation of single-scale optical pulses) and
b) DSR (generation of double-scale optical lumps).

Figure 4 samples pulse trains corresponding to the the identified typical generation regimes. The pulse repetition rate matched the fundamental cavity round-trip time and was equal to 22 MHz. It must be noted that pulses generated in SSR were more stable: the pulse-to-pulse peak power instability did not exceed 2% (see Fig. 4a), whereas in DSR, this parameter was much higher around 20% (Fig. 4b).



a) b)

Fig.4. Pulse trains of two typical generation regimes: a) SSR (generation of single-scale optical pulses) and
b) DSR (generation of double-scale optical lumps).

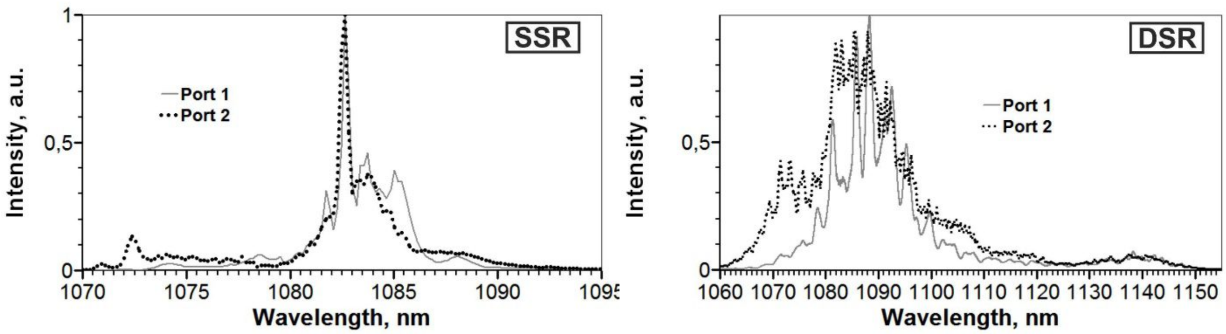
Our experiment has demonstrated that employment of two active media with two independent pump sources not only allows to control the difference in non-linear phase incursion of the two counter-propagating waves within the NALM and to switch between generation regimes, but also leads to relatively high average power of the output radiation. The maximal average radiation power at the laser output Port 1 was 500 and 525 mW for SSR and DSR respectively. At the same time, the average power at the laser output Port 2 amounted to 140 mW (SSR) and 320 mW (DSR). The total output power from both ports in the regime of single-scale optical pulse generation equalled 0.64 W, and in the double-scale optical lump regime it was 0.85 W. In Fig. 5, we present typical optical spectra at Ports 1 and 2 for both pulsed generation regimes SSR and DSR.

The ratio of radiation powers at Port 2 and Port 1 was 0.28 in SSR, which figure matches well the estimates given in[31] for the ratio of radiation powers of single-scale $sech^2$-shaped optical pulses counter-propagating along the passive loop of the resonator.

In DSR, the ratio of radiation power at Port 2 to the corresponding power at Port 1 amounted to 0.61, the proportion of the central narrow ACF peak being 18% (Fig. 2). This is also a good match of the estimates given in[31] for the relation of

Downloaded From: http://proceedings.spiedigitallibrary.org/ on 03/13/2016 Terms of Use: http://spiedigitallibrary.org/ss/TermsOfUse.aspx

the magnitude of the narrow central peak of the double-scale ACF to the ratio of the radiation powers of double-scale optical lumps travelling in the opposite directions along the passive resonator loop.



a) b)

Fig.5. Optical spectra of the radiation exiting from Ports 1 and 2 in two typical regimes of pulsed generation: SSR (a) and DSR (b).

4. CONCLUSION

The present work demonstrates for the first time a method of electronic switching of a fibre laser between generation of single-scale optical pulses and double-scale optical lumps in any direction. This electronic switching was carried out through setting specific values of power launched by two independent pumping sources into two separate active media comprised in NALM. This method was implemented in an all-PM-fibre master oscillator and it allows generation of powerful pulses in both regimes with the maximal average output power around 0.5 W at the pulse repetition rate of 22 MHz. The single-scale optical pulse generation regime resulted in pulses with duration of less than 10 ps (ACF width of 13 ps), whereas in the regime of double-scale optical lump generation, femtosecond clusters were obtained with the envelope width of 16 ps and sub-pulse duration < 200 fs.

Fibre lasers capable of producing both single-scale optical pulses and double-scale optical lumps are very promising radiation sources for research, industrial, and other applications.

ACKNOWLEDGMENTS

This work was supported by the Grants of Ministry of Education and Science of the Russian Federation (agreement No. 14.B25.31.0003, ZN-06-14/2419, order No. 3.162.2014/K); Grant of the Russian Foundation of Basic Research (No. 16-02-00104, 16-32-60160, 16-32-00781); Foundation for Promotion of Small Enterprises in Science and Technology (138AGR/18581).

REFERENCES

[1] Fermann, M. E. and Hart, I., "Ultrafast fibre lasers", Nature Photonics 7, 868–874 (2013).
[2] Tamura, K., Haus, H. A. and Ippen, E. P., "Self-starting additive pulse mode-locked erbium fiber ring laser", Electron. Lett. 28, 2226-2228 (1992).
[3] Kobtsev, S., Smirnov, S., Kukarin, S. and Turitsyn, S., "Mode-locked fiber lasers with significant variability of generation regimes", Optical Fiber Technology 20(6), 615-620 (2014).

Downloaded From: http://proceedings.spiedigitallibrary.org/ on 03/13/2016 Terms of Use: http://spiedigitallibrary.org/ss/TermsOfUse.aspx

[4] Kobtsev, S., Smirnov, S., Kukarin, S., Ivanenko, A., "Extent of parameter variability for different pulses from a passively mode-locked fibre laser", Proc. SPIE 9135, “Laser Sources and Applications II”, 91351K (2014).
[5] Smirnov, S., Kobtsev, S., Kukarin, S. and Ivanenko, A., "Three key regimes of single pulse generation per round trip of all-normal-dispersion fiber lasers mode-locked with nonlinear polarization rotation", Optics Express 20(24), 27447-27453 (2012).
[6] Ilday, F. Ö., Buckley, J., Kuznetsova, L. and Wise, F. W., "Generation of 36-fs pulses from a ytterbium fiber laser", Opt. Exp. 11, 3550 (2003).
[7] Kieu, K.and Wise, F. W., "All-fiber normal-dispersion femtosecond laser", Opt. Express 16 (15), 11453 (2008).
[8] Ivanenko, A.V., Kobtsev, S.M. and Kukarin, S.V., "Femtosecond ring all-fiber Yb laser with combined wavelength-division multiplexer-isolator", Laser Physics 20(2), 344-346 (2010).
[9] Ivanenko, A.V., Kobtsev, S.M., Kukarin, S.V. and Kurkov, A.S., "Femtosecond Er laser system based on side-coupled fibers", Laser Physics 20(2), 341-343 (2010).
[10] Kobtsev, S.M., Kukarin, S.V., Fedotov, Y.S. and Ivanenko, A.V., "High-energy femtosecond 1086/543-nm fiber system for nano- and micromachining in transparent materials and on solid surfaces", Laser Physics 21(2), 308-311 (2011).
[11] Radnatarov, D., Khripunov, S., Kobtsev, S., Ivanenko, A. and Kukarin, S., "Automatic electronic-controlled mode locking self-start in fibre lasers with non-linear polarisation evolution", Optics Express 21(18), 20626-20631 (2013).
[12] Liu, D. F., Zhu, X. J. and Wang, C. H., "High energy giant chirped passively mode-locked Yb^{3+}-doped fiber laser with nanoseconds to picoseconds pulses", Laser Physics 21(2), 414-418 (2011).
[13] Nyushkov, B. N., Denisov, V. I., Kobtsev, S. M., Pivtsov, V. S., Kolyada, N. A., Ivanenko, A.V. and Turitsyn, S. K., "Generation of 1.7-uJ pulses at 1.55um by a self-modelocked all-fiber laser with a kilometers-long linear-ring cavity", Laser Physics Letters 7(9), 661-665 (2010).
[14] Turitsyn, S., Dubov, M., Kobtsev, S. and Ivanenko, A., "Mode-locking in 25-km fibre laser", 36th European Conference on Optical Communication (ECOC), Sep 19-23, 2010, Torino, Italy, Tu.5.D.1.
[15] Nyushkov, B. N., Ivanenko, A. V., Kobtsev, S. M., Turitsyn, S. K., Mou, C., Zhang, L., Denisov, V. I. and Pivtsov, V. S., "Gamma-shaped long-cavity normal-dispersion modelocked Er-fiber laser for sub-nanosecond high-energy pulsed generation", Laser Physics Letters 9(1), 59-67 (2012).
[16] Koliada, N. A., Nyushkov, B. N., Ivanenko, A. V., Kobtsev, S. M., Harper, P., Turitsyn, S. K., Denisov, V.I. and Pivtsov, V.S., "Generation of dissipative solitons in an actively mode-locked ultralong fibre laser", Quantum Electronics 43(2), 95-98 (2013).
[17] Liu, J., Chen, Y., Tang, P., Miao, L., Zhao, C., Wen, S. and Fan, D., "Duration switchable high-energy passively mode-locked Raman fiber laser based on nonlinear polarization evolution", IEEE Photonics J. 7(5), 1503207 (2015).
[18] Kobtsev, S., Kukarin, S. and Fedotov, Y., "Ultra-low repetition rate mode-locked fiber laser with high-energy pulses", Optics Express 16(26), 21936-21941 (2008).
[19] Renninger, W. H., Chong, A. and Wise, F.W., "Dissipative solitons in normal-dispersion fiber lasers", Phys. Rev. A77, 023814 (2008).
[20] Zhang, Z. and Dai, G., "All-normal-dispersion dissipative soliton Ytterbium fiber laser without dispersion compensation and additional filter", IEEE Photonics J. 3(6), 1023-1029 (2011).
[21] Smirnov, S. V., Kobtsev, S. M., Kukarin, S. V. and Ivanenko, A.V., "New regime of single-pulse lasing in fibre lasers with mode locking by nonlinear polarisation evolution", Quantum Electronics 42(9), 781-784 (2012).
[22] Horowitz, M., Barad, Y. and Silberberg, Y., "Noiselike pulses with a broadband spectrum generated from an erbium-doped fiber laser," Opt. Lett. 22(11), 799–801 (1997).
[23] Kobtsev, S., Kukarin, S., Smirnov, S., Turitsyn, S.. and Latkin, A., "Generation of double-scale femto/pico-second optical lumps in mode-locked fiber lasers", Optics Express 17(23), 20707-20713 (2009).
[24] Nie, B., Parker, G., Lozovoy, V. V. and Dantus, M., "Energy scaling of Yb fiber oscillator producing clusters of femtosecond pulses," Opt. Eng. 53, 051505 (2014).
[25] Xia, H., Li, H., Deng, G., Li. J., Zhang, S. and Liu, Y., "Compact noise-like pulse fiber laser and its application for supercontinuum generation in highly nonlinear fiber", Applied Optics 54(32), 9379-84 (2015).
[26] Smirnov, S. V., Kobtsev, S. M., Kukarin, S. V., Turitsyn, S. K. "Mode-Locked Fibre Lasers with High-Energy Pulses" [Laser Systems for Applications], InTech, Chapter 3, 39-58 (2011).
[27] Xu, B., Martinez, A., Yun, S., Chee, S.., Goh, S. and Yamashita, S., "Generation of dissipative solitons and noise-like pulse from figure of eight fiber laser", in Asia Communications and Photonics Conference, OSA Technical Digest (online) (Optical Society of America, 2012), paper ATh2A.2.

Downloaded From: http://proceedings.spiedigitallibrary.org/ on 03/13/2016 Terms of Use: http://spiedigitallibrary.org/ss/TermsOfUse.aspx

[28] Smirnov, S. V., Kobtsev, S. M. and Kukarin, S. V., "Efficiency of non-linear frequency conversion of double-scale pico-femtosecond pulses of passively mode-locked fiber laser," Opt. Express 22(1), 1058-1064 (2014).
[29] Kobtsev, S., Kukarin, S., Smirnov, S. and Ankudinov, I., "Cascaded SRS of single- and double-scale fiber laser pulses in long extra-cavity fiber," Opt. Express 22(17), 20770-20775 (2014).
[30] Fermann, M. E., Haber, F., Hofer, M. and Hochreiter, H., "Nonlinear amplifying loop mirror", Opt. Lett. 15(13), 752–754 (1990).
[31] Fedotov, Y. S., Ivanenko, A. V., Kobtsev, S. M. and Smirnov, S.V., "High average power mode-locked figure-eight Yb fibre master oscillator", Optics Express 22(25), 31379-31386 (2014).

Downloaded From: http://proceedings.spiedigitallibrary.org/ on 03/13/2016 Terms of Use: http://spiedigitallibrary.org/ss/TermsOfUse.aspx