DOCTOR OF PHILOSOPHY

Ultra-long mode-locked Er-droped fibre lasers

Aleksey Ivanenko

2013

Aston University

THE FULL TITLE OF THE THESIS AS AGREED WITH THE SUPERVISOR

ULTRA-LONG MODE-LOCKED ER-DOPED FIBRE LASER

ALEKSEY IVANENKO

Doctor of Philosophy

ASTON UNIVERSITY

October 2012

ASTON UNIVERSITY

UITRA-LONG MODE-LOCKED ER-DOPED FIBRE LASER

Aleksey Ivanenko

Doctor of Philosophy, 2012

ABSTRACT

The development of ultra-long (UL) cavity (hundreds of meters to several kilometres) mode-locked fibre lasers for the generation of high-energy light pulses with relatively low (sub-megahertz) repetition rates has emerged as a new rapidly advancing area of laser physics. The first demonstration of high pulse energy laser of this type was followed by a number of publications from many research groups on long-cavity Ytterbium and Erbium lasers featuring a variety of configurations with rather different mode-locked operations. The substantial interest to this new approach is stimulated both by non-trivial underlying physics and by the potential of high pulse energy laser sources with unique parameters for a range of applications in industry, bio-medicine, metrology and telecommunications.

It is well known, that pulse generation regimes in mode-locked fibre lasers are determined by the intra-cavity balance between the effects of dispersion and non-linearity, and the processes of energy attenuation and amplification. The highest per-pulse energy has been achieved in normal-dispersion UL fibre lasers mode-locked through nonlinear polarization evolution (NPE) for self-mode-locking operation. In such lasers are generated the so-called dissipative optical solitons. The uncompensated net normal dispersion in long-cavity resonators

usually leads to very high chirp and, consequently, to a relatively long duration of generated pulses.

This thesis presents the results of research Er-doped ultra-long (more than 1 km cavity length) fibre lasers mode-locked based on NPE.

The self-mode-locked erbium-based 3.5-km-long all-fiber laser with the 1.7 μJ pulse energy at a wavelength of 1.55 μm was developed as a part of this research. It has resulted in direct generation of short laser pulses with an ultra-low repetition rate of 35.1 kHz. The laser cavity has net normal-dispersion and has been fabricated from commercially-available telecom fibers and optical-fiber elements. Its unconventional linear-ring design with compensation for polarization instability ensures high reliability of the self-mode-locking operation, despite the use of a non polarization-maintaining fibers.

The single pulse generation regime in all-fibre erbium mode-locking laser based on NPE with a record cavity length of 25 km was demonstrated. Mode-locked lasers with such a long cavity have never been studied before. Our result shows a feasibility of stable mode-locked operation even for an ultra-long cavity length.

A new design of fibre laser cavity – "γ-configuration", that offers a range of new functionalities for optimization and stabilization of mode-locked lasing regimes was proposed. This novel cavity configuration has been successfully implemented into a long-cavity normal-dispersion self-mode-locked Er-fibre laser. In particular, it features compensation for polarization instability, suppression of ASE, reduction of pulse duration, prevention of in-cavity wave breaking, and stabilization of the lasing wavelength. This laser along with a specially designed double-pass EDFA have allowed us to demonstrate an environmentally stable all-fibre laser system able to deliver sub-nanosecond high-energy pulses with low level of ASE noise.

Keywords

Ultra-long fibre laser, dissipative solitons, passive mode-locking, ultra-short pulse.

Publications

1) B.N.Nyushkov, A.V.Ivanenko, S.M.Kobtsev, S.K.Turitsyn, C.Mou, L.Zhang, V.I.Denisov, V.S.Pivtsov. Gamma-shaped long-cavity normal-dispersion modelocked Er-fibre laser for sub-nanosecond high-energy pulsed generation. *Laser Physics Letters, v. 9, No. 1, pp. 59-67 (2012).*

2) S.Smirnov, S.M.Kobtsev, S.Kukarin, A.V.Ivanenko. Key regimes of single-pulse generation of fibre lasers mode-locked due to non-linear polarization evolution. *Advanced Photonics Congress, Nonlinear Photonics Conference, OSA Technical Digest (online), Specialty Optical Fibres (SOF) 2012, paper: JM5A.28, 17-21 June 2012, Colorado Springs, Colorado, USA.*

3) N.Koliada, B.Nyushkov, A.Ivanenko, S.Kobtsev, P.Harper, S.Turitsyn, V.Denisov, V.Pivtsov. Dissipative solitons in ultra-long actively mode-locked fibre laser. *15th International Conference "Laser Optics 2012", June 25-29, 2012, St.Petersburg, Russia, ThR1-17.*

4) *S.M.Kobtsev, S.V.Kukarin, Y.S.Fedotov, A.V.Ivanenko. High-Energy Femtosecond 1086/543-nm Fibre System for Nano- and Micromachining in Transparent Materials and on Solid Surfaces. Laser Physics, v. 21, No. 2, pp. 308-311 (2011).*

5) S.Turitsyn, M.Dubov, S.Kobtsev, A.Ivanenko. Mode-Locking in 25-km Fibre Laser. 36th European Conference on Optical Communication (ECOC), Sep 19-23, 2010, Torino, Italy, Tu.5.D.1

6) B.Nyushkov, V.Denisov, S.Kobtsev, V.Pivtsov, N.Kolyada, A.Ivanenko, S.Turitsyn. High-pulse-energy mode-locked 3.5-km-long Er fibre laser. 14th

International Conference "Laser Optics 2010", June 28 - July 02, 2010, St.Petersburg, Russia, FrR1-38.

7) B.N.Nyushkov, V.I.Denisov, S.M.Kobtsev, V.S.Pivtsov, N.A.Kolyada, A.V.Ivanenko, S.K.Turitsyn. Generation of 1.7-uJ pulses at 1.55um by a self-modelocked all-fibre laser with a kilometers-long linear-ring cavity. Laser Physics Letters, v. 7, N9, pp. 661-665 (2010).

8) A.V.Ivanenko, S.M.Kobtsev, S.V.Kukarin, A.S.Kurkov. Femtosecond Er laser system based on side-coupled fibres. Laser Physics, v. 20, N2, pp. 341-343 (2010).

9) A.V.Ivanenko, S.M.Kobtsev, S.V.Kukarin. Femtosecond ring all-fibre Yb laser with combined wavelength-division multiplexer-isolator. Laser Physics, v. 20, N2, pp. 344-346 (2010).

10) A.S.Kurkov, A.I.Ivanenko, S.M.Kobtsev, S.V.Kukarin. CW and pulsed lasers based on Er-doped GTWave fibre. 17th Int. Conference on Advanced Laser Technologies, Antalya, Turkey, 26 Sep - 01 Oct 2009, Conf. Proc. p. 93.

ACKNOWLEDGEMENTS

I would like to express my utmost gratitude to Prof. Sergey Turitsyn, my supervisor, for guiding me through the whole doctoral program, for furthering my passion for physics and for improving my personality.

My sincere appreciation goes to Dr Vladimir Mezentsev, Dr Michael Dubov, Dr Sergey Sergeev who helped me get started in the lab and gave me many illuminating thoughts and discussions and helped me in my research project.

I want to express special gratitude to Dr Boris Nyushkov of the Institute of Laser Physics Siberia Branch of Russian Academy of Sciences (Russia, Novosibirsk)for valuable advice and productive cooperation and assistance in carrying out the research work.

I would like to express my gratefully acknowledge to Dr Sergey Kobtsev of the Novosibirsk State University (Russia, Novosibirsk) for valuable advice, guidance for valuable advice and productive cooperation and assistance in carrying out the work and assistance in my work.

I send my special thanks to Dr Elena Turitsyna for keeping me company in the Photonics Research Group of the Aston University, for helping me through this academic exploration and for helping me in resolving any life problems.

Many thanks, to Mr Bert Biggs for extensive technical support.

Thanks also go to those people who helped me in my research project: Drs of the Aston University: Ural Akhmetshin, Atalla El-taher, Paul Harper and Drs of the Novosibirsk State University (Russia, Novosibirsk): Sergey Smirnov, Sergey Kukarin, Yuriy Fedotov.

In addition, I want to thank the rest of my group members, Dr Alexey Lanin, Dmitry Sitnokov, Dr Aleksander Stepanenko, Dr Stas Derevyanko, Vladimir Gainov, Dr Dmitry Churkin, Chengbo Mou for many pleasurable moments in the lab.

I would like to thank Dr Thomas Allsop for the Saturday debates and many interesting ideas.

My gratefully acknowledge to my all other colleagues from Aston University, Novosibirsk State University (Russia, Novosibirsk) and Institute of Laser Physics Siberia Branch of Russian Academy of Sciences (Russia, Novosibirsk)for helping me in research project.

Last but not the least; I would like to thank my wife, my daughter and parents for their endless love and support.

TABLE OFCONTENTS

1. Introduction.

Nowadays, lasers have become ubiquitous devices equally important in fundamental science, engineering technologies and in a range of practical applications. In the last decade there has been a revolutionary progress in laser science fuelled by advances in high-power systems, ultra-short pulse lasers and oscillators with high pulse energy. The progress was driven by a variety of new important applications that these advanced laser systems can open-up. This expansion has been facilitated by continuous advances in material science, achievements in technology and by the improvement in our understanding of the fundamental laser principles and physical effects underlying the operation and performance of new types of lasers.

Solid-state and fibre femtosecond lasers is the base of such high-power ultra-short pulse systems. These lasers have wide linear spectra due to generating large numbers of equidistant longitudinal locking modes and this spectrum can extend from infra-red to ultraviolet. Correlated with reference frequency standard such frequency comb can be used as reference frame for precision spectroscopic measuring and optical methods of different physical value measuring and also for transfer characteristics of optical standards in the radio-frequency region for optical clock realization [1, 2].

As compared with traditional lasers based on bulk elements fibre femtosecond lasers are more compact and reliable and have a higher coefficient of efficiency. The central wavelength of fibre erbium lasers lies in the spectral range 1,5 – 1,6 um which is traditional for fibre-optic communication line. Of a special interest are all-fibre femtosecond lasers without precision optomechanical elements, because the cavities of such lasers are not subjected to misalignment due to vibrations, mechanical and thermal relaxation processes. Therefore the mode-locking regime in all-fibre femtosecond lasers is very stable [2, 3].

The recent rapid development of the physics and technology of fibre lasers as well as vast expansion of their application areas greatly stimulate the quest for and the study of more advanced operational modes of such lasers, including generation of ultra-short and high-energy pulses. Since the invention of the laser researchers have continuously strived to generate shorter laser pulses. Simultaneously achieving a short duration and high pulse energy is, certainly, more challenging than improving one of these parameters independently. However, it is this combination that becomes increasingly important in a wide range of scientific, technological, medical, and other applications. High energies and ultra-short pulse durations are both associated with high field intensity that often makes physical system nonlinear. In fibre lasers, there are specific properties relevant to both shortening of the pulse duration and increasing their energy. The main obstacles on the road to shorter pulses are a relatively high dispersion and non-linearity of fibre resonators. In addition, the path to high-energy ultra-short pulses is, typically, further complicated by relatively low energy damage thresholds of the standard fibre components, such as splitters, isolators, and others. While the effects of dispersion can be compensated by different rather advanced means, the nonlinear effects in fibre are much more difficult to control. Thus, nonlinearity plays a critical role in the design of advanced fibre laser systems, but paradoxically, it is somewhat undesirable to many engineers because of its very limited tractability. Substantial efforts have been made to reduce resonator nonlinearity, e.g. by using large mode area fibres and this direction presents an important modern trend in laser technology. On the other hand, the understanding and mastering of nonlinear physical fibre systems has the potential to enable a new generation of laser concepts. Therefore, it is of great importance to study physics and engineering design of laser systems based on nonlinear photonic technologies. In particular, new nonlinear concepts and solutions pave a way for development of advanced mode-locked fibre lasers with ultra-short high-energy pulses.

Presently, passive mode locking is one of the key methods of ultra-short pulse (USP) generation. As recently as few years ago, femto- and pico-second pulses extracted directly from the master oscillator operating passive mode-locking regime had relatively low energies, typically, not exceeding at few dozens of nJ and some special cases hundreds of nJ. In order to radically boost the pulse energy, additional optical amplifiers were used or, indeed, completely different method of short pulse generation, Q-switch was employed, which allowed considerably higher per-pulse energy, albeit at the expense of longer duration, typically, over several nanoseconds and more [].

The combined Q-switching and mode-locking in one cavity has also been successfully employed for generation of high-energy pulses of laser radiation (Lin et al 2008, Jabczyński et al, 2006). Another way to increase per-pulse energy of output radiation is the cavity dumping technique (Johnson et al, 1976), which can be used in all the mentioned above types of lasers. In the cavity dumping method, in order to increase intra-cavity pulse energy, it is used a multi-path closed resonator, into which a so-called cavity dumper is inserted that allows picking single high-energy pulses out of the cavity at a frequency lower than the original pulse repetition rate. More powerful pump sources may also increase per-pulse energy in passively mode-locked lasers, but this may be achieved with certain combinations of pulse and cavity parameters only (Akhmediev et al, 2008; Chang et al, 2008). Another method traditionally utilised in most high-energy laser systems of different types relies on extra-cavity optical amplification.

Compared to Q-switching and cavity dumping techniques, mode-locked lasers allow a post-compression of output pulses, making possible generation of ultra-short optical pulses with high energy [4-23].The length of the resonator is, indeed, an important design parameter in mode-locked laser being responsible for repetition rate of generated pulses and their per-pulse energy. Higher per-pulse energy E_p of the output in mode-locked lasers (at the same average power P_{ave} of radiation) may be achieved by direct extension of the laser cavity, since $E_p \propto P_{ave} T_R \propto P_{ave}\, nL/c$ (c is the speed of light, n-refractive index) - pulse energy is directly proportional to cavity length L and round trip time T_R, while the repetition rate is inversely proportional to the resonator length.

On the Fig. 1 is showed pulses train of two fibre mode-locked lasers with different length but with the same average output power. The upper pulses train corresponded to the laser with shorter cavity length. While the second laser can has more pulse duration due to higher the intracavity dispersion this laser has higher pulse energy due to higher the cavity length. This technique has following advantages:

1. More pulse stability.
2. Low repetition rate.
3. Shorter pulse duration.
4. Ease of realization in fibre lasers.

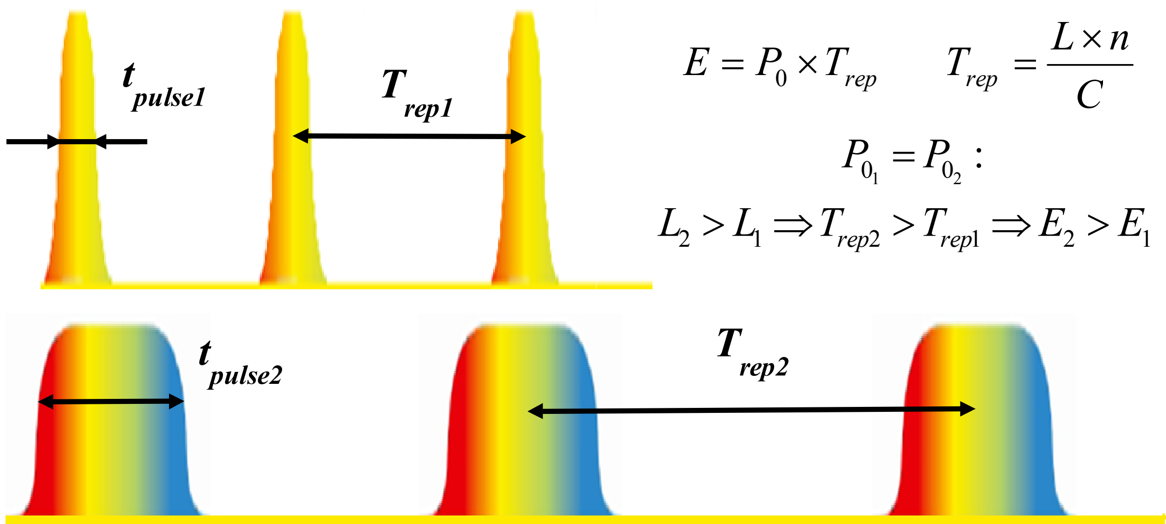

Fig. 1. *Explaining of increasing pulse energy by extension of the cavity length of mode-locked laser.*

In the case of CW fibre lasers, it has been recently demonstrated that resolvable resonator modes can be observed in a cavity as long as impressive 270 km [24]. However, the underlying physics of operation of mode-locked fibre lasers is very different from stable operation of CW fibre lasers. The extension of the cavity length and corresponding increase of per-pulse energy in long mode-locked lasers is a challenging physical and engineering problem. First experiments demonstrated stable passive mode locking in relatively long resonators with lengths up to 100 m and 400 m were carried out with solid-state [25] and with fibre [27-27] lasers. The reduction of the pulse repetition rate by the order of magnitude down to a few MHz scale and the corresponding increase of per-pulse energy by the same factor (at the fixed average output power) have been demonstrated.

The next level was achieved in the breakthrough works [4] in mode-lock fibre lasers with a several km cavities. Other examples of passive mode locking in fibre lasers with > 1 km resonators have been demonstrated in the subsequent works[6-9, 11, 12, 15]. Such a dramatic elongation of the laser resonator led to more than two orders of magnitude increase in the output pulse energy at the same pump power. At ultra-low (for mode-locked lasers) pulse repetition rate (37 kHz) and pulse duration of 10 ns, the energy per pulse reached 4 μJ in 8 km (optical length) fibre laser cavity [5].

The first demonstration of high pulse energy laser of this type [4] was followed by a number of publications from many research groups on long-cavity Ytterbium and Erbium lasers featuring a variety of configurations with rather different mode-locked operations [5-23].

Nowadays, the development of long-cavity (hundreds of meters to several kilometers) passively mode-locked fibre lasers for the generation of high-energy light pulses with relatively low (sub-megahertz) repetition rates has emerged as a new rapidly advancing area of laser physics. The substantial interest to this new approach is stimulated both by non-trivial underlying physics and by the potential of high pulse energy laser sources with unique parameters for a range of applications in industry, bio-medicine, metrology and telecommunications.

At present, the highest pulse energy achieved in long-cavity fibre lasers was demonstrated in systems, exploiting the effect of nonlinear polarization evolution (NPE) for self-mode-locking operation. In lasers of this type, the pulse energy of several microJoules was demonstrated [4, 6, 13, 16] without using any traditional methods such as Q-switching or cavity dumping techniques. In lasers using saturable absorbers, e.g. conventional semiconductor saturable absorber mirrors (SESAMs) [7-9, 22] or substances based on carbon nano-tubes [10, 17], the maximal pulse energy does not exceed several dozens of nanoJoules. This can be explained both by limited modulation capabilities of these absorbers and by the peculiarities of the dynamics of pulsed generation in high-energy long-cavity fibre lasers. Long-cavity pulsed fibre lasers based on the non-linear optical loop mirrors (NOLM) also feature relatively small pulse energies [5,23].

It is well known, that pulse generation regimes in mode-locked fibre lasers are determined by the intra-cavity balance between the effects of dispersion and non-linearity, and the processes of energy attenuation and amplification. In case when the dissipation plays a decisive role in the pulse dynamics, e.g. in fibre lasers with normal intra-cavity dispersion, it is possible to generate the so-called dissipative optical solitons [28-30]. The combination of dissipative soliton lasing and laser cavity lengthening makes possible a considerable increase in the pulse energy with a corresponding reduction in the repetition rate, at the same time preserving stable mode-locking operation with one pulse per cavity period. On the other hand, the uncompensated net normal dispersion in long-cavity resonators usually leads to the high chirp [10, 11] and, consequently, to a relatively long duration of generated pulses. Moreover, long-cavity normal-dispersion fibre lasers mode-locked via NPE may tend to a noise-like regime generating double-scale optical lumps [31] with a smooth bell-shaped envelope and stochastic ultra-short pulsed filling, unless a careful adjustment of the laser system parameters is implemented. In all cases the observed duration either of single pulses or double-scale lumps in long-cavity pulsed lasers with normal dispersion varies from few to dozens of nanoseconds. Recently proposed and theoretically studied method of extra-cavity dispersive compression of output pulses of such lasers opens a prospect of producing pulses with sub-nanosecond duration without significant reduction in their energy [32].

In long-cavity mode-locked fibre lasers with anomalous dispersion [5, 12, 14, 17] it is possible to generate substantially shorter, typically, picosecond scale pulses. However, their energy is low, typically not exceeding 20 nJ. Further energy growth is limited by nonlinear effects leading to pulse decomposition and transition to multi-pulse generation mode. The related limitations of pulse shaping in anomalous-dispersion mode-locked fibre lasers are explained in [2] and [**Ошибка! Источник ссылки не найден.**]. Nevertheless, with a proper resonator management, as demonstrated recently, it is feasible to generate high-energy pulses even in long-cavity fibre lasers with anomalous dispersion. However, these high-energy pulses possess properties similar to those of dissipative solitons and have a relatively long (nanosecond) duration as well [19, 20].

The development of novel types of long-cavity mode-locked fibre lasers for the low-repetition-rate generation of wave-breaking-free high-energy pulses with sub-nanosecond duration presents significant challenge with great potential for a range of applications.

This thesis presents the results of research Er-doped ultra-long (more than 1 km cavity length) fibre lasers mode-locked based on NPE.

1. We have developed self-mode-locked erbium-based 3.5-km-long all-fiber laser with the 1.7 μJ pulse energy at a wavelength of 1.55 μm. It has resulted in direct generation of short laser pulses with an ultra-low repetition rate of 35.1 kHz. The laser cavity has netnormal-dispersion and has been fabricated from commercially-available telecom fibers and optical-fiber elements. Its unconventional linear-ring design with compensation for polarization instability ensures high reliability of the self-mode-locking operation, despite the use of nonpolarization-maintaining fibers.

2. We have demonstrated single pulse generation regime in all-fibre erbium mode-locking laser based on NPEwith a record cavity length of 25 km.

Mode-locked lasers with such a long cavity have never been studied before. Our result shows a feasibility of stable mode-locked operation even for an ultra-long cavity length.

3. We have proposed a new design of fibre laser cavity – "γ-configuration", that offers a range of new functionalities for optimization and stabilization of mode-locked lasing regimes. This novel cavity configuration has been successfully implemented into a long-cavity normal-dispersion self-mode-locked Er-fibre laser. In particular, it features compensation for polarization instability, suppression of ASE, reduction of pulse duration, prevention of in-cavity wave breaking, and stabilization of the lasing wavelength. This laser along with a specially designed double-pass EDFA have allowed us to demonstrate an environmentally stable all-fibre laser system able to deliver sub-nanosecond high-energy pulses with low level of ASE noise.

Reference

1. Hall J.L. Rev. Mod. Phys., **78** (4), 1279 (2006).
2. Haensh T.W. Rev. Mod. Phys., **78** (4), 1297 (2006).
3. L. E. Nelson et al., Ultrashort-pulse fibre ring lasers//Appl. Phys. B 65, 277-294 (1997).
4. A. M.Zheltikov.Ultrashort Pulseand Methods of Nonlinear Optics (Nauka, Moscow, 2006) [in Russian].
5. S. Kobtsev, S. Kukarin, and Y. Fedotov, "Ultra-low repetition rate mode-locked fibre laser with high-energy pulses," Opt. Express **16**, 21936-21941 (2008).http://www.opticsinfobase.org/abstract.cfm?URI=oe-16-26-21936

6. B. Ibarra-Escamilla, O. Pottiez, E. A. Kuzin, R. Grajales-Coutino, and J. W. Haus, “Experimental investigation of a passively mode-locked fibre laser based on a symmetrical NOLM with highly twisted low birefringence fibre," Laser Phys. **18**, 914–919 (2008).http://www.springerlink.com/content/txq40u0622286221/
7. S. Kobtsev, S. Kukarin, S. Smirnov, A. Latkin, and S. Turitsyn. *Proceedings of the European Conference on Lasers and Electro-Optics (CLEO/Europe-EQEC 2009),* Munich, Germany, 2009, CJ8.4
8. X. Tian, M. Tang, P. Shum, Y. Gong, C. Lin, S. Fu, and T. Zhang, "High-energy laser pulse with a submegahertz repetition rate from a passively mode-locked fibre laser," Opt. Lett. **34**, 1432-1434 (2009).http://www.opticsinfobase.org/ol/abstract.cfm?uri=ol-34-9-1432
9. X. Tian, M. Tang, X. Cheng, P. Shum, Y. Gong, and C. Lin, "High-energy wave-breaking-free pulse from all-fibre mode-locked laser system," Opt. Express **17**, 7222-7227 (2009). http://www.opticsinfobase.org/abstract.cfm?uri=oe-17-9-7222
10. M. Zhang , L. Chen, C. Zhou, Y. Cai, L. Ren, Z. Zhang, “Mode-locked ytterbium-doped linear-cavity fibre laser operated at low repetition rate,” Laser Phys. Lett. **6**, 657-660 (2009).http://onlinelibrary.wiley.com/doi/10.1002/lapl.200910047/abstract
11. E. J. R. Kelleher, J. C. Travers, E. P. Ippen, Z. Sun, A. C. Ferrari, S. V. Popov, and J. R. Taylor, "Generation and direct measurement of giant chirp in a passively mode-locked laser," Opt. Lett. **34**, 3526-3528 (2009).http://www.opticsinfobase.org/abstract.cfm?uri=ol-34-22-3526
12. E. J. R. Kelleher, J. C. Travers, Z. Sun, A. G. Rozhin, A. C. Ferrari, S. V. Popov and J. R. Taylor, Appl. Phys. Lett. **95**, 111108 (2009)

13. L. Chen, M. Zhang, C. Zhou, Y. Cai, L. Ren, Z. Zhang, “Ultra-low repetition rate linear-cavity erbium-doped fibre laser modelocked with semiconductor saturable absorber mirror,” Electronics Lett. **45**, 731-733 (2009).http://scitation.aip.org/getabs/servlet/GetabsServlet?prog=normal&id=ELLEAK000045000014000731000001&idtype=cvips&gifs=yes&ref=no

14. S. M. Kobtsev, S. V. Kukarin, S. V. Smirnov, Y. S. Fedotov, “High-energy mode-locked all-fibre laser with ultralong resonator,” Laser Phys. **20**, 351-356 (2010).http://www.springerlink.com/content/g510823212856871/

15. V.I. Denisov, B.N. Nyushkov, V.S. Pivtsov, “High-energy pulses at a very low repetition rate from a self-mode-locked all-fibre erbium laser with large normal cavity dispersion,” Proc. SPIE **7580**, 75802U (2010).http://spiedigitallibrary.org/proceedings/resource/2/psisdg/7580/1/75802U_1?isAuthorized=no

16. V. Denisov, B. Nyushkov, V. Pivtsov, "Self-mode-locked all-fibre erbium laser with a low repetition rate and high pulse energy," Quantum Electron. **40**, 25-27 (2010).http://iopscience.iop.org/1063-7818/40/1/A05

17. B.N. Nyushkov, V.I. Denisov, S.M. Kobtsev, V.S. Pivtsov, N.A. Kolyada, A.V. Ivanenko, and S.K. Turitsyn, “Generation of 1.7-uJ pulses at 1.55um by a self-modelocked all-fibre laser with a kilometers-long linear-ring cavity,” Laser Phys. Lett. **7**, 661-665 (2010).http://onlinelibrary.wiley.com/doi/10.1002/lapl.201010037/abstract

18. Y. Senoo, N. Nishizawa, Y. Sakakibara, K. Sumimura, E. Itoga, H. Kataura, and K. Itoh, "Ultralow-repetition-rate, high-energy, polarization-maintaining, Er-doped, ultrashort-pulse fibre laser using single-wall-

carbon-nanotube saturable absorber," Opt. Express **18**, 20673-20680 (2010).http://www.opticsinfobase.org/abstract.cfm?URI=oe-18-20-20673

19. L.J. Kong, X.S. Xiao, and C.X. Yang, "Low-repetition-rate all-fibre all-normal-dispersion Yb-doped mode-locked fibre laser," Laser Phys. Lett. **7**, 359–362 (2010).http://onlinelibrary.wiley.com/doi/10.1002/lapl.200910162/abstract
20. X. Li, X. Liu, X. Hu, L. Wang, H. Lu, Y. Wang, and W. Zhao, "Long-cavity passively mode-locked fibre ring laser with high-energy rectangular-shape pulses in anomalous dispersion regime," Opt. Lett. **35**, 3249-3251 (2010).http://www.opticsinfobase.org/abstract.cfm?uri=ol-35-19-3249
21. D. Mao, X. Liu, L. Wang, H. Lu, and H. Feng, "Generation and amplification of high-energy nanosecond pulses in a compact all-fibre laser," Opt. Express **18**, 23024-23029 (2010).http://www.opticsinfobase.org/abstract.cfm?uri=oe-18-22-23024
22. J.-H. Lin, D. Wang, and K.-H. Lin, "High energy pulses generation with giant spectrum bandwidth and submegahertz repetition rate from a passively mode-locked Yb-doped fibre laser in all normal dispersion cavity," Laser Phys. Lett. **8**, 66–70 (2011).http://onlinelibrary.wiley.com/doi/10.1002/lapl.201010084/abstract
23. R. Song, H. Chen, S. Chen, J. Hou and Q. Lu, "A SESAM passively mode-locked fibre laser with a long cavity including a band pass filter," J. Opt. 13, 035201 (2011).
24. F. Ai, Z. Cao, X. Zhang, C. Zhang, B. Zhang, B. Yu, "Passively mode-locked fibre laser with kilohertz magnitude repetition rate and tunable pulse width," Optics & Laser Technology **43**, 501-505 (2011).

25. S. K. Turitsyn, J. D. Ania-Castañón, S. A. Babin, V. Karalekas, P. Harper, D. Churkin, S. I. Kablukov, A. E. El-Taher, E. V. Podivilov, and V. K. Mezentsev, Phys. Rev. Lett. **103** 133901 (2009).
26. V. Z. Kolev, M. J. Lederer, and B. Luther-Davies, A. V. Rode, Opt. Lett. **28**, 1275 (2003).
27. J. U. Kang, R. Posey, R. D. Esman, Opt. Lett. **23**, 1375 (1998).
28. K. H. Fong, S. Y. Set, and K. Kikuchi, in*Proceedings of IEEE/OSA Optical Fibre Conference (OFC) 2007,* Anaheim, 2007, OTuF2.
29. N. Akhmediev and A. Ankiewicz (eds.), Dissipative Solitons, Lecture Notes in Physics, Springer Series, Vol. 661 (Springer, Berlin/Heidelberg, 2005).
30. W.H. Renninger, A. Chong, and F.W. Wise, "Dissipative solitons in normal-dispersion fibre lasers," Phys. Rev. A**77**, 023814 (2008).http://pra.aps.org/abstract/PRA/v77/i2/e023814
31. G.P. Agrawal, Nonlinear Fibre Optics, Second ed. (Academic Press, New York, 1995).
32. S. Kobtsev, S. Kukarin, S. Smirnov, S. Turitsyn, and A. Latkin, "Generation of double-scale femto/pico-second optical lumps in mode-locked fibre lasers," Opt. Express **17**, 20707-20713 (2009).http://www.opticsinfobase.org/oe/abstract.cfm?uri=oe-17-23-20707
33. B.N. Nyushkov, I.I. Korel, V.I. Denisov, V.S. Pivtsov and N.A. Kolyada, "Sub-nanosecond high-energy pulses from ultra-long mode-locked erbium fibre lasers," Proc. SPIE 7994, 799406 (2010).http://spiedigitallibrary.org/proceedings/resource/2/psisdg/7994/1/799406_1?isAuthorized=no

2. Laser physics.

There are several basic techniques for the pulse generation. The main methods are the Q-switching, the cavity dumping and the mode-locking. Consider these methods in more details.

2.1. Q-switching

Q switching is a technique for obtaining energetic short (but not ultrashort) pulses from a laser by modulating the intracavity losses and thus the *Q* factor of the laser resonator. The technique is mainly applied for the generation of nanosecond pulses of high energy and peak power with solid-state bulk lasers [1].

Q-switching is achieved by putting some type of variable attenuator inside the laser's optical resonator. When the attenuator is functioning, light which leaves the gain medium does not return, and lasing cannot begin. This attenuation inside the cavity corresponds to a decrease in the *Q factor* or *quality factor* of the optical resonator. A high Q factor corresponds to low resonator losses per round trip, and vice versa (Fig. 1). The variable attenuator is commonly called a "Q-switch", when used for this purpose.

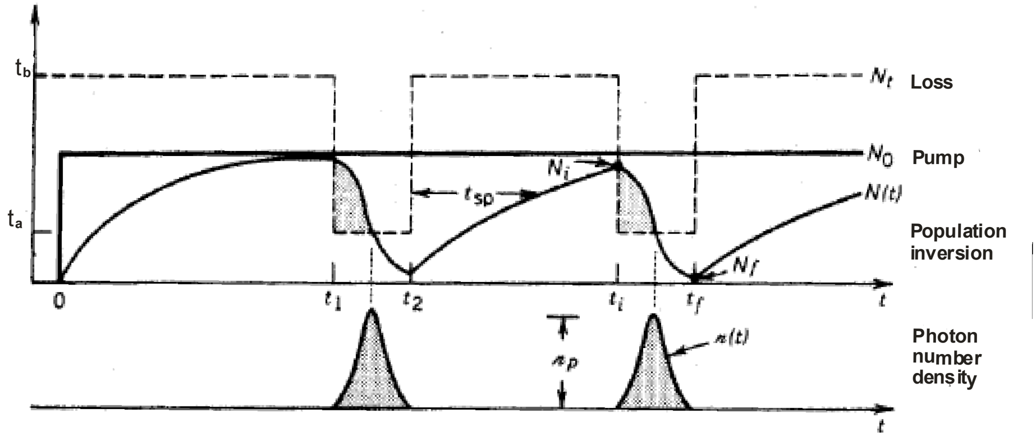

Fig. 2.1. *Operation of a Q-switched laser. Variation of the population threshold Nt (which is proportional to the resonator loss). The pump parameter No, the population difference N(t), and the photon number (t).*

The generation of a Q-switched pulse (sometimes called a **giant pulse**) can be described as follows [1, 2]:

- Initially, the resonator losses are kept at a high level. As lasing cannot occur at that time, the energy fed into the gain medium by the pumping mechanism accumulates there. The amount of stored energy is often limited only by spontaneous emission (particularly for continuous pumping), in other cases (with strong enough gain) by the onset of lasing or strong ASE, if not simply by the pump energy available. The stored energy can be a multiple of the saturation energy.
- Then, the losses are suddenly (with active or passive means, see below) reduced to a small value, so that the power of the laser radiation builds up very quickly in the laser resonator. This process typically starts with noise from spontaneous emission, which is amplified to macroscopic power levels within hundreds or thousands of resonator round trips.

- Once the temporally integrated intracavity power has reached the order of the saturation energy of the gain medium, the gain starts to be saturated. The peak of the pulse is reached when the gain equals the remaining (low) resonator losses. The large intracavity power present at that time leads to further depletion of the stored energy during the time where the power decays. In many cases, the energy extracted after the pulse maximum is similar to that before the pulse maximum.

The pulse duration achieved with Q switching is typically in the nanosecond range (corresponding to several resonator round trips), and usually well above the resonator round-trip time. The energy of the generated pulse is typically higher than the saturation energy of the gain medium and can be in the millijoule range even for small lasers. The peak power can be orders of magnitude higher than the power which is achievable in continuous-wave operation. Even for lasers with moderate size and with moderate focusing of the beam, the peak intensity can be sufficient for optical breakdown in air.

In most cases, Q-switched lasers generate regular pulse trains via **repetitive Q switching**. The pulse repetition rate is typically in the range from 1–100 kHz, sometimes higher. Passively Q-switched microchip lasers have reached pulse durations far below 1 ns and repetition rates up to several megahertz, whereas large (typically amplified) laser systems can deliver pulses with many kilojoules of energy and durations in the nanosecond range.

Lasers to which the Q-switching technique is applied are called **Q-switched lasers**. Q-switching was first proposed in 1958 by Gordon Gould [3], and independently discovered and demonstrated in 1961 or 1962 by R.W. Hellwarth and F.J. McClung using electrically switched Kerr cell shutters in a ruby laser [4].

Various Technical Issues

Doped insulator solid-state lasers are most suitable for Q switching, since their gain media have long upper-state lifetimes and high saturation energies, and hence the capability to store large amounts of energy. Bulk lasers are normally preferable over fiber lasers, since their larger mode areas allow more energy to be stored, and their shorter resonators allow for shorter pulses.

For both active and passive Q switching, higher pulse repetition rates usually imply longer pulses. This is because the reduced pulse energy leads to a weaker modulation of the net gain, and thus to a slower rise and decay of the optical power. When the pulse repetition rate of an actively Q-switched laser falls below the inverse upper-state lifetime, the maximum pulse energy is achieved, but the average power is reduced due to increased losses via fluorescence (spontaneous emission).

Pumping does not have to occur in a continuous-wave fashion; it is also possible to use pulsed pumping with flash lamps or quasi-cw laser diodes, fired shortly before the Q switch is opened. This reduces the energy losses via spontaneous emission and thus allows the use of gain media with shorter upper-state lifetimes.

In most cases, the pulses in a Q-switched laser are generated by amplifying noise from spontaneous emission in many resonator round trips. Therefore, there is usually no phase correlation between subsequent pulses, and the pattern of excited resonator modes can be random. Moreover, excitation of multiple modes results in the generation of beat notes, apparent as fast modulations on the Q-switched pulse envelope. In some cases, however, a Q-switched laser is seeded e.g. with the output of a small single-frequency seed laser in order to obtain a low-noise single-frequency output, avoiding beat notes and reducing the noise overall (→ **injection seeding**). It is also possible to generate such a seed in the laser itself (**self-injection seeding**) from **prelasing** at a low power level.

The nonlinear dynamics of Q switching sometimes lead to unexpected phenomena, such as the generation of double pulses and/or certain instabilities. Numerical simulations of pulse generation can be very helpful in understanding such effects and identifying the right cure.

In some laser applications, such as laser marking, the Q-switched pulse train must be switched off for certain time intervals. This often introduces the problem that the first pulse has a higher energy, if the pump source is continuously operated during the time without pulse emission. Various methods have been developed to solve or mitigate this problem.

Note that the high pulse energies and peak powers obtained with Q switching can raise serious laser safety issues even for lasers with fairly small average output power. Also, the optical intensities can become high enough to destroy intracavity optical elements such as laser mirrors. It can therefore be necessary to use a resonator design which avoids any strongly focused beams on optical components – which can be challenging particularly for short laser resonators (as are desirable for short pulses) with large mode areas. Further, a Q-switched laser has to be kept very clean in order to avoid the burning of dust particles.

2.2. Cavity Dumping

Cavity dumping is a technique for pulse generation which can be combined either with Q switching or with mode locking, or sometimes even with both techniques at the same time. In any case, the basic idea is to keep the optical losses of the laser resonator as low as possible for some time, so that an intense pulse builds up in the resonator, and then to extract this pulse within about one cavity round-trip time using a kind of optical switch ("cavity dumper"), such as an acousto-optic modulator or a Pockels cell [1, 5].

Cavity Dumping for Nanosecond Pulses

Originally, cavity dumping was invented in the context of Q-switched lasers. The purpose is to eliminate some basic limitations of Q switching. In particular, it can be disturbing that the pulse duration achievable with a Q-switched laser increases when the pulse repetition rate is increased; this is a consequence of the lower laser gain for a lower stored energy in the gain medium. Also, Q switching with high repetition rates may lead to pulse dropout.

The modification for cavity dumping is essentially that the resonator contains only highly reflecting mirrors (i.e., no partially trans missive output coupler mirror), and output coupling is controlled with the optical modulator in the resonator [10,11]. Typically, this is an acousto-optic modulator, which is turned on briefly for pulse extraction and then diffracts the intracavity beam into the output (see Fig. 2.2).

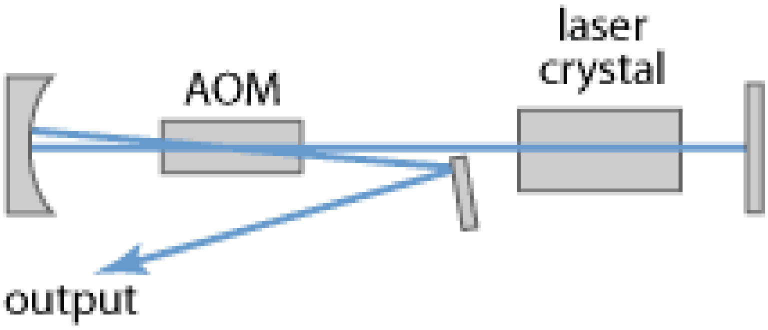

Fig. 2.2. *Schematic setup of a cavity-dumped laser. The acousto-optic modulator (AOM) is turned on only briefly when a pulse is extracted. At other times, the light can circulate in the resonator with low losses [1].*

The pulse formation then works as follows:

- First, the modulator is kept in a state where most of the light in the resonator is coupled out, so that lasing cannot occur because the device is below the laser threshold. The energy provided by the pump source is then largely stored in the gain medium, as in a Q-switched laser.
- The modulator is then switched to a state where light circulating in the laser resonator experiences only the small parasitic losses. As a result, the intracavity power builds up quickly – typically, within a few hundred resonator round-trip times. No light is coupled out during that period.
- Then, the modulator is again quickly switched into the state where most of the light is coupled out. The light in the resonator is thus extracted within about one round-trip time. After that, a new cycle can begin.

A notable difference from Q switching is that before generation of the output pulse the energy is stored in the intracavity light field, rather than in the gain medium. The perhaps most important advantage is that this energy can be extracted within just one round-trip time, independent of the time required for building up the intracavity power. Therefore, the pulse duration achievable is more or less determined by the resonator length (provided that the switching time of the modulator is no longer than the resonator round-trip time), and is decoupled from the laser gain. This means that even for very high pulse repetition rates of e.g. several megahertz, pulse durations of a few nanoseconds are still achievable. In this regime, a Q-switched laser would generate much longer pulses, or would even not be able to generate one pulse for each intended time slot. (Pulse dropouts can occur when the Q switch is operated at too high frequencies.)

For high pulse repetition rates (well above the inverse upper-state lifetime, a cavity-dumped laser operates particularly stably, since some light always remains in the laser resonator after pulse extraction, and this light can act as a seed for the next pulse. This is the preferred operation regime.

Although the laser setup for cavity dumping is in principle similar to that for Q switching, the requirements particularly concerning the Q switch are different:

- The switching time should not be longer than the resonator round-trip time, i.e., it should usually not exceed a few nanoseconds (while Q switching works well with much lower switching speeds). For acousto-optic modulators, this requires not only that the RF source can be quickly switched, but also that the beam radius in the modulator is fairly small, since the switching time is limited by the transit time of the acoustic wave through the laser beam. Unfortunately, a small mode area increases the optical intensities in the modulator and may require additional intracavity optics.
- The diffraction efficiency should be high, ideally well above 50%, so that most of the light can be extracted within one resonator round-trip. For that reason, acousto-optic cavity dumpers are often operated with higher RF

frequencies of several hundred megahertz, as compared with tens of megahertz for Q switches, and use relatively high RF powers.

From these considerations it follows that cavity dumping is superior to Q switching mainly for high pulse repetition rates, particularly if short pulse durations are required at the same time. On the other hand, this technique introduces additional constraints e.g. on mode areas and switching speeds.

Cavity Dumping of Ultrashort Pulses

Cavity dumping can also be used in mode-locked lasers for generating ultrashort pulses with higher pulse energies [6-9]. As for nanosecond devices, the resonator losses are kept small for most of the time, so that the circulating pulse can become intense. When it has reached the maximum intensity (and stable pulse parameters), this intracavity pulse can be coupled out with an optical switch. The switching speed required is then even higher than for nanosecond devices. Therefore, an electro-optic modulator in combination with a polarizer is usually required (Fig. 2.3.). In addition, the switching must be synchronized with the circulating pulse: a fast photodiode monitors the weak pulses leaking e.g. through a highly reflecting cavity mirror, and the driver electronics use this signal to fire the optical switch at the right time, so that the switching occurs while the pulse is at the other end of the resonator. The pulse duration achievable is in that case, of course, not limited by the round-trip time; a long round-trip time can even be beneficial because it reduces the requirements concerning the switching time.

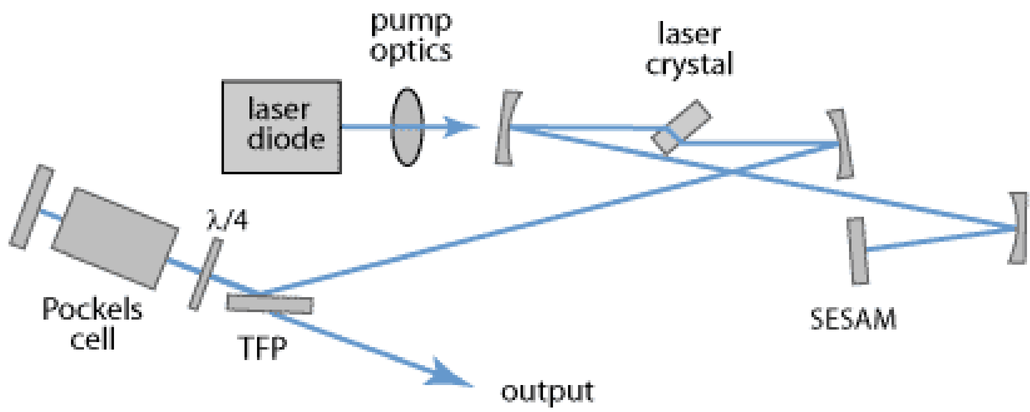

Fig. 2.3. *Schematic setup of a cavity-dumped picosecond laser. The cavity dumper contains a Pockels cell, a quarter-wave plate, and a thin-film polarizer (TFP [1]).*

Cavity dumping for ultrashort pulses is mostly used with mode-locked solid-state bulk lasers, such as titanium–sapphire lasers or diode-pumped neodymium-doped or ytterbium-doped lasers. The achieved pulse energy is typically about an order of magnitude higher than with an ordinary mode-locked laser (i.e., typically of the order of 1 μJ), and the pulse repetition rate can be hundreds of kilohertz or several megahertz. The average output power of cavity-dumped lasers is usually significantly smaller than for a mode-locked laser without cavity dumper; this is due to the effect of parasitic resonator losses.

Problems

The design of a cavity-dumped laser, particularly for ultrashort pulse generation, is not a trivial issue. Apart from the aspect of fast and well synchronized switching, problems can arise e.g. from ringing of the Pockels cell or from the optical nonlinearity and chromatic dispersion introduced by the cavity dumper. The greatly varying intracavity pulse energy is also not compatible with soliton mode locking. Therefore, it is usually not advisable to consider a cavity dumper as a simple add-on to an independently designed mode-locked laser. Instead, the system as whole should be properly designed, taking into account e.g. the effect of the nonlinearity of the cavity dumper on the pulse formation from the very beginning.

For higher pulse energies, lower pulse repetition rates may be considered. However, cavity dumping then no longer works very well: when the intracavity power really vanishes between two extracted pulses, the stability of the process is degraded. For similar reasons, it is also not easy to combine cavity dumping with mode locking and simultaneous Q switching: whereas Q switching can quickly build up a high power in the resonator, the mode-locking process requires much more time to form stable pulses. For low repetition rates (e.g. for 10 kHz or lower) with correspondingly higher pulse energies, regenerative amplifiers are preferable, where the pulse formation and the amplification process are decoupled.

2.3. Mode-locking.

Mode locking [12] is a method (or actually a group of methods) to obtain ultrashort pulses from lasers, which are then called **mode-locked lasers**. Here, the laser resonator contains either an active element (an optical modulator) or a nonlinear passive element (a saturable absorber), which causes the formation of an ultrashort pulse circulating in the laser resonator. In the steady state, the various effects influencing the circulating pulse are in a balance so that the pulse parameters are unchanged after each completed round trip, or often even nearly constant throughout each round trip. Each time the pulse hits the output coupler mirror, a usable pulse is emitted, so that a regular pulse train leaves the laser. Assuming a single circulating pulse, the pulse repetition period corresponds to the resonator round-trip time (typically several nanoseconds), whereas the pulse duration is much lower: typically between 30 fs and 30 ps, in extreme cases down to ≈ 5 fs. For that reason, the peak power of a mode-locked laser can be orders of magnitude higher than the average power [1].

The synchronization of the longitudinal modes of the laser cavity is used to generate of ultrashort pulse lasers.

At the same phase imposed on all longitudinal modes of the laser, the in-phase addition of the amplitudes of electric fields leads to the generation of ultrashort pulses, the duration of which is limited by the width of the lasing spectrum [13].

The idea of locking was proposed and implemented in 1964 [14, 15]. The first experiments were carried out on gas lasers [14, 16-18]. Mode locking in these studies was carried out by an active modulation of the resonator parameters (loss optical length) at the intermode beat frep ≈ c / Σnl (where c - speed of light in vacuum, n - refractive index of the fiber core, l - length of the fiber). Experimentally in the laser were obtained continuous sequence of short pulses with a typical duration of 600 ps and a duty cycle equal to the round-trip time of radiation in the resonator, which was consistent with the well-developed theoretical concepts [15, 19, 20].

More simple and accessible method of generation of ultrashort pulses was self-synchronization (passive mode) modes, which arises when incorporated in the laser cavity saturable filter. This method was used almost immediately received ultrashort pulses with durations that are close to the limit [21-33], and the intensities of the order of 1010 W/cm2. This led to the fact that in subsequent research efforts were focused mainly on clarifying the nature of technology and the improvement of passive mode-locking [24-30].

Upon receipt of ultrashort pulses in fiber lasers used similar techniques as in the classical solid-state lasers based on three-dimensional elements: synchronous pumping, active and passive mode locking.

Passive mode locking in fiber lasers can be divided into two types - forced (passive mode locking due to the saturable absorbers, such as a semiconductor saturable absorber mirror (SESAM) [31] or carbon nanotubes), and self-synchronization, based on the so-called effect of the nonlinear polarization evolution (NPE) (using a polarization controller and a member with the polarization-dependent transmission [32]).

Today, developed by saturable absorbers such as carbon nanotubes or SESAM deposited on the fiber end, in principle, does not require any additional adjustable elements. However, the use of saturable absorbers, a limitation on the pulse energy associated with limited modulation capabilities of sinks and the breakdown of themselves saturable absorbers. When synchronization modes due to the nonlinear evolution of the polarization of the pulses can occur in a wider range of peak capacity [31, 32].

One of the most interesting from a scientific point of view, but also important for practical applications of laser systems feature a passively mode-locked due to the effect of the NPE is the possibility of lasing in a lot of different modes [34].

Fiber laser mode-locked by the NPE are more promising in terms of practical applications, such as lasers have better energy performance and provide greater freedom in tuning the parameters of output radiation (the ability to change the shape and duration of the pulse shape of the optical spectrum), and also possible to generate pulses of different modes synchronization modes depending on the setting of the polarization controller.

Theory of the mode-locking.

The mechanism of self-mode owes its existence to a strong phase modulation of the radiation due to the occurrence noticeable nonlinear addition to the refractive index in the active element at the time of passage through it of a powerful light pulse (optical Kerr effect [19]). Self-phase modulation (SPM) is the dominant nonlinear mechanism, leading to a spectral broadening of pulsed light in the fiber. It is a direct consequence of the dependence of the refractive index of quartz glass radiation intensity [35]. Given the dependence of the intensity of the refractive index may be written as:

$n(t) = n_0+n_2I(t)$,

where I - the radiation intensity in the fiber, n0 - linear component of the refractive index, n2 - the refractive index of the nonlinear coefficient (so-called Kerr coefficient) defined as follows:

$$n_2 = \frac{3}{8}\frac{1}{n}\mathrm{Re}(\chi^{(3)}).$$

In silica fibers typical coefficient n2 is about ~ 3 • 10-16 cm2 / W. Thus, the nonlinear component becomes significant only at very high intensities.

The electric field of pulsed light propagating in the fiber (for simplicity) can be simplified as shown:

$$U(z,t) = A(t)e^{-i(\omega_0 t-\beta z)}.$$

where A (t) - the function of the envelope (slowly varying amplitude), ω0 - carrier frequency, β - the propagation constant in the fiber. The product βz determines the phase Φ:

$$\Phi = -\beta z = -\omega \frac{n}{c} z.$$

Due to the Kerr nonlinearity (the nonlinear coefficient of the refractive index n2), extending along the fiber pulsed radiation homing tests, time-dependent, nonlinear phase shift ΦNL:

$$\Phi_{NL}(z,t) = -\frac{z\omega_0 n_2}{c} |A(t)|^2.$$

This changes the electric field of radiation in accordance with the transformation:

$$U(z,t) \to U(z,t) e^{i\phi_{NL}}$$

The nonlinear dependence of the phase change from time to time the instantaneous frequency is usually denoted by the term "frequency chirp", which is proportional to the time derivative of ΦNL:

$$\Delta\omega_{NL}(t) = -\frac{d\Phi_{NL}}{dt} = -\frac{l\omega_0 n_2}{c} \cdot \frac{d|I(t)|}{dt}$$

where l - length of the fiber; I (t) = | A (t) | 2 - intensity propagating radiation. Thus, the instantaneous frequency can be expressed as ω (t) = ω0 + ΔωNL (t).

This means that the propagation of the pulse through the fiber radiation in the spectrum of the pulses arise new frequency components, and therefore, the spectrum broadens. Despite the fact that SPM broadens the spectrum of the pulse, the temporal envelope of the function remains unchanged. Fig. 2.4 illustrates the spectral broadening caused by SPM Gaussian pulse.

Aston University

Illustration removed for copyright restrictions

Fig. 2.4. *Spectral broadening of a Gaussian pulse for different values of the nonlinear phase shift ΦNLmax caused by SPM [13].*

The effect of nonlinear rotation of the polarization ellipse is that the evolution of the polarization state of light propagating in the optical fiber depends on the intensity of the radiation. The nonlinear evolution of the polarization state - is the result of the combined action of strong Kerr nonlinearity (optical Kerr effect [35]: $n = n + n2I$) and weak birefringence:.

The effect of the nonlinear evolution of the polarization state is shown at the condition of weak birefringence: $Dn \sim I \cdot n2$.

As a result of the change of state of polarization (rotation of the polarization ellipse) is different for waves with different amplitudes (Fig. 2.5).

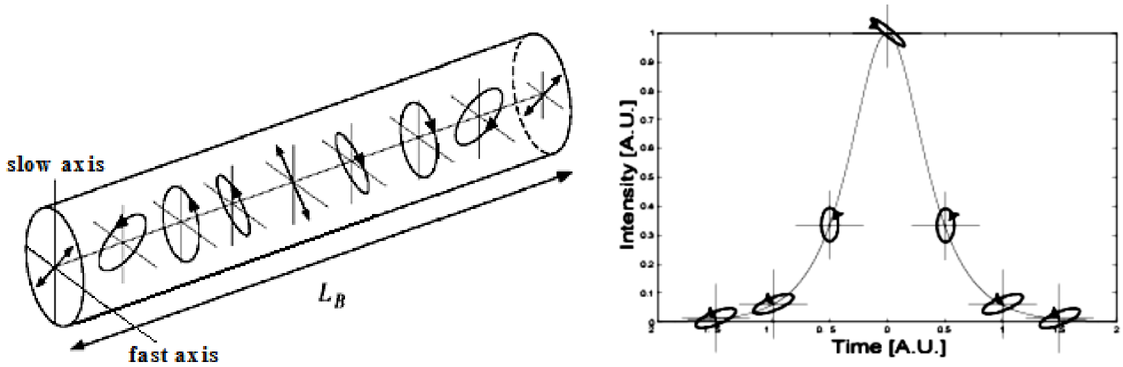

Fig. 2.5. *Evolution of the polarization state of the pulse propagation along the fiber, and the polarization dependence of the intensity.*

If the fiber resonator element placed polarization dependence of the transmission (e.g., a polarizer), the resulting amplitude modulation mechanism can be used for self-locking (Fig. 2.6).

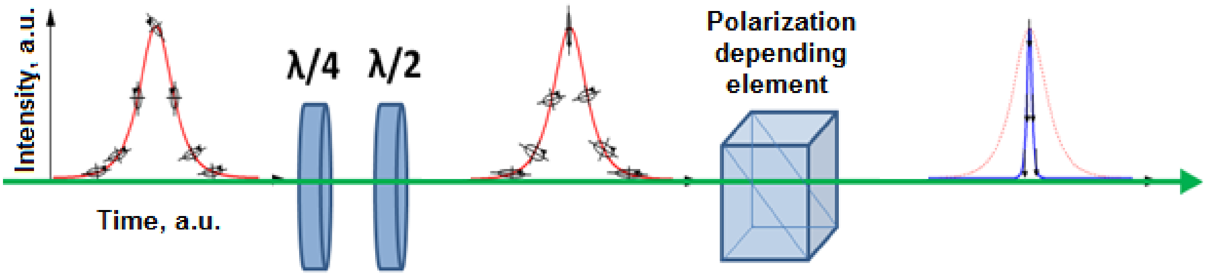

Fig. 2.6. *Evolution of the polarization state of the pulse propagation along the fiber, and the polarization dependence of the intensity.*

Reference

1. http://www.rp-photonics.com/q_switching.html
2. R. Paschotta, *Field Guide to Laser Pulse Generation*, SPIE Press, Bellingham, WA (2007)
3. Taylor, Nick (2000). *LASER: The inventor, the Nobel laureate, and the thirty-year patent war*. New York: Simon & Schuster. ISBN 0-684-83515-0. p. 93.
4. McClung, F.J. and Hellwarth, R.W.: "Giant optical pulsations from ruby". *Journal of Applied Physics* 33 3, 828-829 (1962).
5. A. A. Vuylsteke *et al.*, “Theory of laser regeneration switching”, J. Appl. Phys. 34 (6), 1615 (1963)
6. G. N. Gibson *et al.*, “Electro-optically cavity-dumped ultrashort-pulse Ti:sapphire oscillator”, Opt. Lett. 21 (14), 1055 (1996)
7. A. Baltuška *et al.*, “All solid-state cavity dumped sub-5-fs laser”, Appl. Phys. B 65, 175 (1997)
8. A. Killi *et al.*, “Diode-pumped femtosecond laser oscillator with cavity dumping”, Opt. Lett. 29 (11), 1288 (2004)
9. A. Killi *et al.*, “High speed electro-optical cavity dumping of mode-locked laser oscillators”, Opt. Express 13 (6), 1916 (2005)
10. L. McDonagh *et al.*, “47 W, 6 ns constant pulse duration, high-repetition-rate cavity-dumped Q-switched TEM_{00} $Nd:YVO_4$oscillator”, Opt. Lett. 31 (22), 3303 (2006)
11. M. Grishin, “Cavity dumping versus stationary output coupling in repetitively Q-switched solid-state lasers”, J. Opt. Soc. Am. B 28 (3), 433 (2011)

12. W. E. Lamb Jr., “Theory of an optical laser”, Phys. Rev. 134 (6A), A1429 (1964).
13. G.P. Agrawal, Nonlinear Fibre Optics, Second ed. (Academic Press, New York, 1995).
14. *L. E. Hargrove*, R. L. *Fork* and M. A. *Pollack*, "*Locking of He-Ne laser modes induced by synchronous intracavity modulation*", App. Phys. Lett., vol. *5*, *no*. *1*, pp. *4-5*, Jul. *1964*.
15. Di Domenico M. “Small signal analysis in internal (coupling type) modulation of laser”. J. Appl. Phys., 1964, v. 35, No 10, p. 2870-2876.
16. M.H. Crowell., “ Characteristics of mode coupled lasers”. IEEE J. Quant. Electron., 1965, v. QE-1, No 1, p. 12-20.
17. S.E. Harris, R. Targ, “FM oscillation of He-Ne laser”. Appl. Phys. Lett., 1964, v. 5, No 11, p. 202-204.
18. E.O. Ammann, blcïvlurtry B.J., Oshman L.K. Detailed experiments on He-Ne lasers. IEEE J. Quant. Electron., 1965, v. QE-1, No 6, p. 263-272.
19. *S. E. Harris* and *O. P. McDuff*, "*Theory* of FM *laser oscillation*", *IEEE* J. *Quantum Electron*., vol. *QE-1*, pp.*245 - 262* , *1965*.
20. A. *Yariv*: "*Internal* *modulation* in *multimode laser* oscillators," *J. Appl. Phys*., *36,* pp. *388-391,* (*1965*).
21. W. H.*Glenn*, Jr., and *M. J. Brienza*, “*Time evolution of picosecond optical pulses*,” *Appl.Phys*. *Lett*., vol. *10*, *pp*. *221-224*, April 15,. *1967*.
22. Т.Н. Кузнецова, В.И. Малышев, А.С. Маркин, “Самосинхронизация аксиальных мод в лазере с просветляющимся фильтром”. ЮТФ, 1967, т. 52, вып. 2, с. 438-446.

23. С.Д. Кайтмазов, И.К. Красюк, П.П. Пашинин, А.М. Прохоров, “Характеристики ОКГ, работающего в режиме с синхронизацией мод”. ДАН СССР, 1968, т. 180, № 6, с. I33I-I332.

24. *A. J. DeMaria*, *W. H. Glenn*. *Jr*.. M. J. *Brienza*, and M. E. Mack,. “*Picosecond laser pulses*.“ *Proc*. *IEEE*, vol. *57*, pp. *2-25*, January. *1969.*

25. *P*. G. *Kryukov* and *V. S. Letokhov*, “*Fluctuation mechanism* of *ultrashort pulse generation* by *laser* with *saturable absorber*,”. *IEEE J*. *Quantum Electron*., 1972, v. QE-8, No 10, p. 766-782.

26. *Б.Я. Зельдович*, *Т.Т. Кузнецова*, “*Генерация сверхкоротких импульсов света* с*помощью лазеров”*, УФН, *Т. 106*, *Вып*. 1, с *47-84*,*1972*.

27. “Сверхкороткие световые импульсы” (под ред. С.Шапиро), Москва, Мир, 1981.

28. Херман Й, Вильгельми Б. “Лазеры сверхкоротких световых импульсов”, Москва, Мир, 1986.

29. Diels J.-C., Rudolph W. “Ultrashort laser pulse phenomena: fundamentals, techniques, and applications on femtosecond time scale”, Boston, Academic Press, 1996.

30. Claude Rulliere, ed., “Femtosecond Laser Pulses”, Berlin, Heidelberg, Springer-Verlag, 1998.

31. N. Haverkamp, H. Yundertmark, C. Fallnich, H.R. Telle, “Frequency stabilization of mode-locked Erbium fiber laser using pump power control”, Applied Physics B 78, 2004

32. L.E. Nelson, D.J. Jones, K. Tamura, H.A. Haus, and E.P. Ippen, “Ultrashort-pulse fiber ring lasers,“Appl. Phys. B 65, 277–294 (1997).

33. B.N. Nyushkov, V.I. Denisov, S.M. Kobtsev, V.S. Pivtsov, N.A. Kolyada, A.V. Ivanenko, and S.K. Turitsyn, "Generation of 1.7-microjoule pulses at

1.55 micron by a self-mode-locked all-fiber laser with a kilometers-long linear-ring cavity", Laser Physics Letters, Vol. 7, No. 9, pp.661-665 (2010).

34. S.Kobtsev, S.Kukarin, S.Smirnov, S.Turitsyn, A.Latkin. Generation of double-scale femto/pico-second optical lumps in mode-locked fiber lasers. Optics Express, v. 17, N 23, pp. 20707-20713 (2009).

35. B. Agate, C. Brown, W. Sibbett, K. Dholakia. Femtosecond optical tweezers for in-situ control of two-photon fluorescence // Opt. Express. – 2004. – V. 12. – P. 3011-3017.

3. Fibre lasers

Create fiber lasers is one of the most striking achievements of quantum electronics. The first fiber laser was established in 1963 ин Snitzer as an active element used glass fibers containing neodymium ions. However, the creation of modern high and compact fiber lasers became possible only giving the benefit of the development in the early 70-ies of optical glass fibers with low optical losses (less than 1 dB km-1 in the near-infrared region) and the subsequent rapid development of fiber-optic telecommunications.

The advantages of fiber lasers over other types include [1]:

- Light is already coupled into a flexible fiber: The fact that the light is already in a fiber allows it to be easily delivered to a movable focusing element. This is important for laser cutting, welding, and folding of metals and polymers.
- High output power: Fiber lasers can have active regions several kilometers long, and so can provide very high optical gain. They can support kilowatt levels of continuous output power because of the fiber's high surface area to volume ratio, which allows efficient cooling.
- High optical quality: The fiber's waveguiding properties reduce or eliminate thermal distortion of the optical path, typically producing a diffraction-limited, high-quality optical beam.
- Compact size: Fiber lasers are compact compared to rod or gas lasers of comparable power, because the fiber can be bent and coiled to save space.

- Reliability: Fiber lasers exhibit high vibrational stability, extended lifetime, and maintenance-free turnkey operation.
- High peak power and nanosecond pulses enable effective marking and engraving.
- The additional power and better beam quality provide cleaner cut edges and faster cutting speeds.
- Lower cost of ownership.

Simple Er fiber lasers with ultrashort pulses are known for the 1990s. Nowadays, a wide variety of fiber lasers with different active media, with different types of resonators, with different characteristics of lasing was developed and continue to develop of new types of fiber lasers to improve their performance.

Next, we consider the main types of configurations and fiber elements needed to create ultrashort pulses erbium-doped fiber lasers.

3.1. Types schematic configurations and solutions resonator fiber lasers.

Fiber lasers can be divided into two classes according to the length of the resonator: 1) short (conventional fiber lasers with cavity lengths up to hundreds of meters), and 2) long and extra-long (hundreds of meters long and kilometers).

There is quite a large variety of types of configurations resonators used both short and long in fiber lasers. In the first class of fiber lasers are the most common fiber lasers with two types of configurations of cavities fiber laser with a ring resonator with a linear resonator. In turn, they both may be made in all-fibre structure [1, 2], and with a gap [3, 4]. All-fibre lasers, unlike lasers discontinuity consist entirely of the fiber components and the design does not contain any adjustable optomechanical elements.

Ring all-fibre unidirectional cavity scheme is the most simple and does not require any reflective elements, which simplifies the creation of all-fibre laser (laser without large opto-mechanical elements).

In the case of a linear configuration with a break, due to external moving mirror surround provides a smooth change in the cavity length in a fairly large range, allowing you to fine tune the pulse repetition frequency to the desired value. As is known, in the manufacture of lasers all-fibre technologically impossible to sustain a desired length of the resonator with high accuracy. In addition, the range of variation due to the repetition frequency of stretching the fiber is very small, amounting to a few hundred hertz. If necessary, fine-tune the frequency of repetition has to make a break and use the adjustable opto-mechanical items.

Lasers with a ring and a linear configuration has its advantages and disadvantages. The main advantage of a ring resonator configuration all-fibre is high resistance mode locking, due to lack of opto-mechanical components and due to the lack of a standing wave (in the regime of cavity traveling wave). While the linear resonator configuration with a gap allows you to get a slightly larger value of the fundamental repetition frequency (150 MHz), and also gives her the ability to accurately adjust a large enough range.

Another interesting solution is a combined schematic - linear and ring cavity laser. This scheme allows you to combine the advantages of circular and linear laser types (traveling wave mode, the ability to adjust the length of the resonator, the possibility of high repetition rate, ease of setup).

Most of the ultra-long lasers are based on the conventional ring configuration - the simplest to set up and requiring no reflectors. Lasers based on NOLM, respectively, have figure-eight cavities. Lasers using SESAM for mode locking, typically utilize linear Fabry-Perot [5, 6] or ring-linear cavity layouts with a short linear arm [7-9]. Of a particular interest is the linear-ring cavity design [10, 11], in which a longer section of the optical fibre is in the linear arm ended by a Faraday mirror. This solution ensures suppression or elimination of polarization-induced fluctuations, thus improving the stability of laser output parameters when low cost non-polarization-maintaining fibres are used. Besides, the linear-ring configuration can provide almost a factor-of-two advantage in the output pulse energy using the same physical length of the resonator due to repetition rate being twice as low as that in a traditional ring laser of the same length. Another original solution was demonstrated in an long-cavity laser [12] fabricated with the use of polarization-maintaining fibres. The pulse repetition rate in such "θ-configuration" resonator is twice as low as in a conventional ring laser of the same fibre length.

3.2. Optical elements of fiber lasers.

Any cavity laser (fiber or bulk solid-state elements) is constructed from the active environment and mirrors, locking resonator. In this case, the cavity must be arranged output portion of the generated radiation. In addition, the cavity should include an element that allows to introduce pump light into the cavity.

Fiber laser with a linear resonator must contain the following elements - a pair of Bragg gratings as mirrors, locking cavity (also through a lattice can enter the pump radiation, and through the second can be arranged emission output of the laser cavity) and the length of the active fiber.

In a ring resonator fiber does not require any additional mirrors. However, in such resonators is desirable to install an optical isolator for reducing the noise level and to ensure unidirectional lasing. In addition, such resonators should contain fiber multiplexer - to enter the pump light into the cavity, as well as the tap - for some of the radiation output of the cavity.

To ensure the synchronization modes due to the effect of nonlinear polarization evolution of fiber lasers as ring resonators, and with linear polarization dependent must contain an element of polarization controllers.
Consider the basic elements of which are built on fiber lasers.

3.2.1. Fiber Brag Grating

A fiber Bragg grating (FBG) is a type of distributed Bragg reflector constructed in a short segment of optical fiber that reflects particular wavelengths of light and transmits all others. This is achieved by creating a periodic variation in the refractive index of the fiber core, which generates a wavelength specific dielectric mirror. A fiber Bragg grating can therefore be used as an inline optical filter to block certain wavelengths, or as a wavelength-specific reflector [13].

The fundamental principle behind the operation of a FBG is Fresnel reflection. Where light traveling between media of different refractive indices may both reflect and refract at the interface.

The refractive index will typically alternate over a defined length. The reflected wavelength (λ_B), called the Bragg wavelength, is defined by the relationship,

$$\lambda_B = 2n_e\Lambda$$

where n_e is the effective refractive index of the grating in the fiber core and Λ is the grating period.

The effective refractive index quantifies the velocity of propagating light as compared to its velocity in vacuum. n_e depends not only on the wavelength but also (for multimode waveguides) on the mode in which the light propagates. For this reason, it is also called modal index.

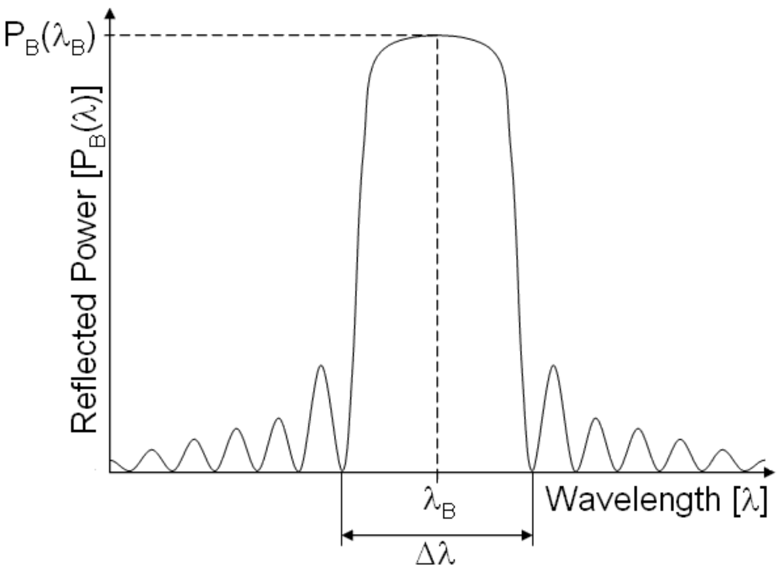

Fig. 3.1. *FBGs reflected power as a function of wavelength [13].*

The wavelength spacing between the first minima (nulls, see Fig. 3.1), or the bandwidth ($\Delta\lambda$), is (in the strong grating limit) given by,

$$\Delta\lambda = \left[\frac{2\delta n_0 \eta}{\pi}\right] \lambda_B$$

where δn_0 is the variation in the refractive index ($n_3 - n_2$), and η is the fraction of power in the core.

Note that this approximation does not apply to weak gratings where the grating length, L_g, is not large compared to $\lambda_B \setminus \delta n_0$.

The peak reflection ($P_B(\lambda_B)$) is approximately given by,

$$P_B(\lambda_B) \approx \tanh^2 \left[\frac{N\eta(V)\delta n_0}{n} \right]$$

where N is the number of periodic variations.

The full equation for the reflected power ($P_B(\lambda)$), is given by,

$$P_B(\lambda) = \frac{\sinh^2 \left[\eta(V)\delta n_0 \sqrt{1 - \Gamma^2} \frac{N\Lambda}{\lambda} \right]}{\cosh^2 \left[\eta(V)\delta n_0 \sqrt{1 - \Gamma^2} \frac{N\Lambda}{\lambda} \right] - \Gamma^2}$$

where,

$$\Gamma(\lambda) = \frac{1}{\eta(V)\delta n_0} \left[\frac{\lambda}{\lambda_B} - 1 \right]$$

3.2.2. Gain medium

Depending on the active medium, fiber lasers can generate radiation at different wavelengths (Fig. 3.2). Fiber lasers with active media doped with ytterbium (Yr3 +) can generate powerful laser radiation up to several kW due to the effective pumping of such media powerful diode lasers at a wavelength of 980 nm. The lasing wavelength fiber laser is in the range 1.0 - 1.1 microns, which is optimum for cutting aluminum and metal alloys. Fiber lasers on ions Tm3 + Ho3 + are used to generate radiation in the mid-infrared wavelength range (1.9-2.1mkm). Lasers on stimulated Raman scattering (SRS) can generate radiation over a wide wavelength range due to the nonlinear frequency conversion. In 2005, was received continuous generation of radiation in the spectral range of 1140 - 1300 nm at the output of the fiber laser with an active fiber doped bismuth (Bi) [14].

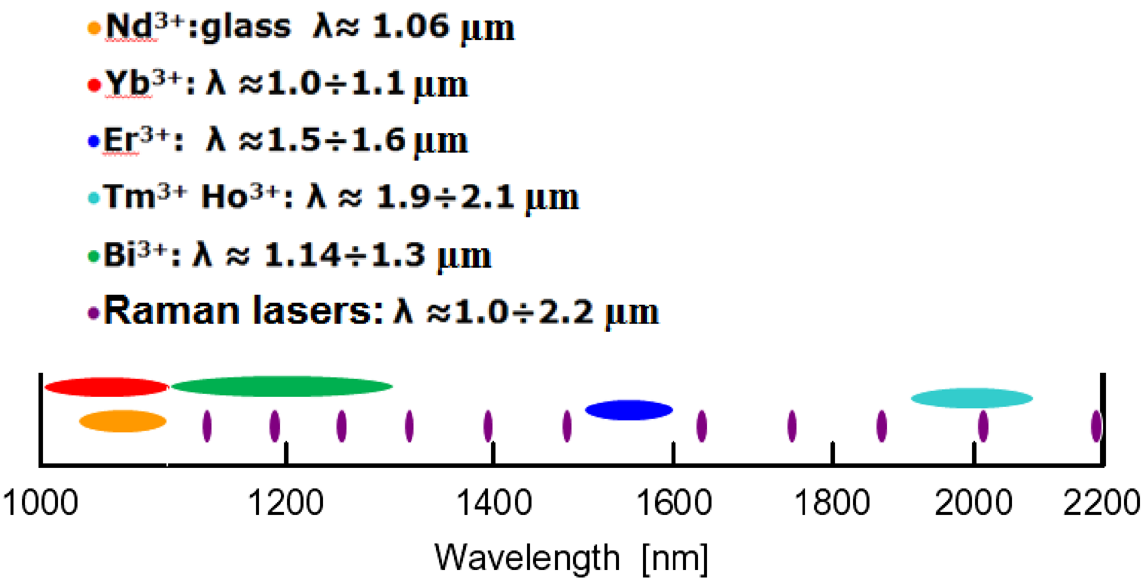

Fig. 3.2. *Wavelengths of fiber lasers with different active media.*

For telecommunications and metrological purposes are the most suitable lasers and usilitili to the active fiber doped with Er. Spectral range Er fiber laser is in the range 1.5-1.6 microns corresponding operating range fiber optic link. Erbium laser has a 3-level scheme of the pump (Fig. 3.3). The pump can operate at two wavelengths of 980 nm and 1480 nm.

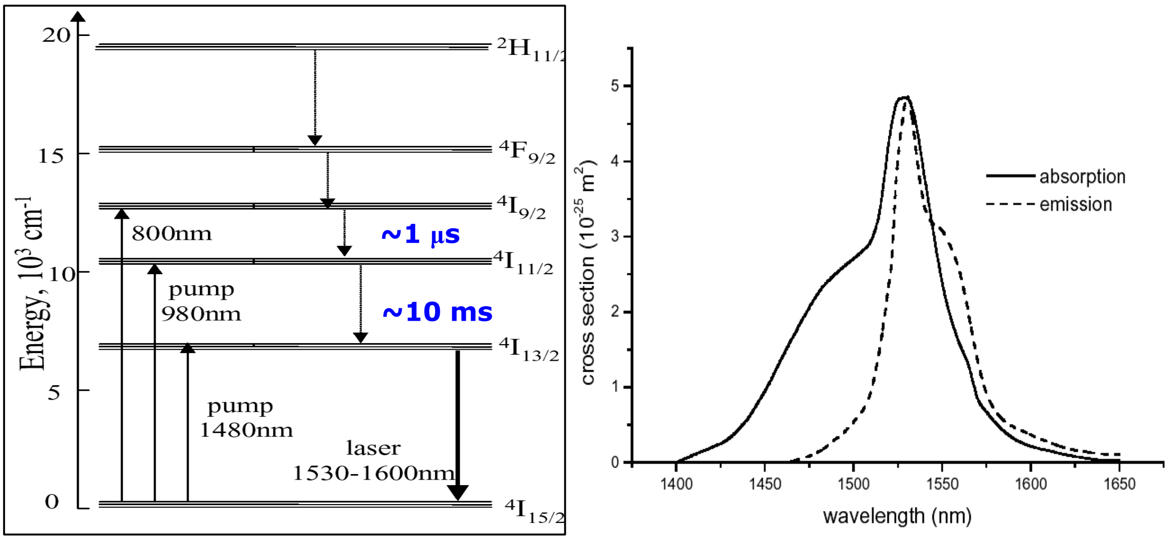

Fig. 3.3. *Schematic of the laser levels and the spectrum of absorption and luminescence Er environments.*

3.2.3. WDM

Wave apparatus (spectral) sealing WDM - WDM filter - functions as multiplexing MUX (association) or demultiplexing DEMUX (separation or filtration) optical signals of different wavelengths - channel - in a single fiber of fibers or multiple fibers of one of several fibers [13]. These devices are distributed in the signal light depending on the wavelength. The multiplexer is used to transmit multiple optical signals (each at its wavelength) in a single fiber. The multiplexers are used in lasers for the introduction of the pump radiation into the laser cavity. The multiplexers are constructed from driftwood technology as well as fiber splitters/couplers.

3.2.4. *Coupler*

Fused couplers are used to split optical signals between two (or more) fibers or to combine optical signals from two (or more) fibers into one fiber. They are constructed by fusing and tapering the fibers together. This method creates a simple, rugged, compact method of splitting or combining optical signals.

These devices are bidirectional and offer low back reflection and insertion losses. 2x2 or 1x2 ports couplers with 10-30% split are used usual for output of laser radiations of fiber laser.

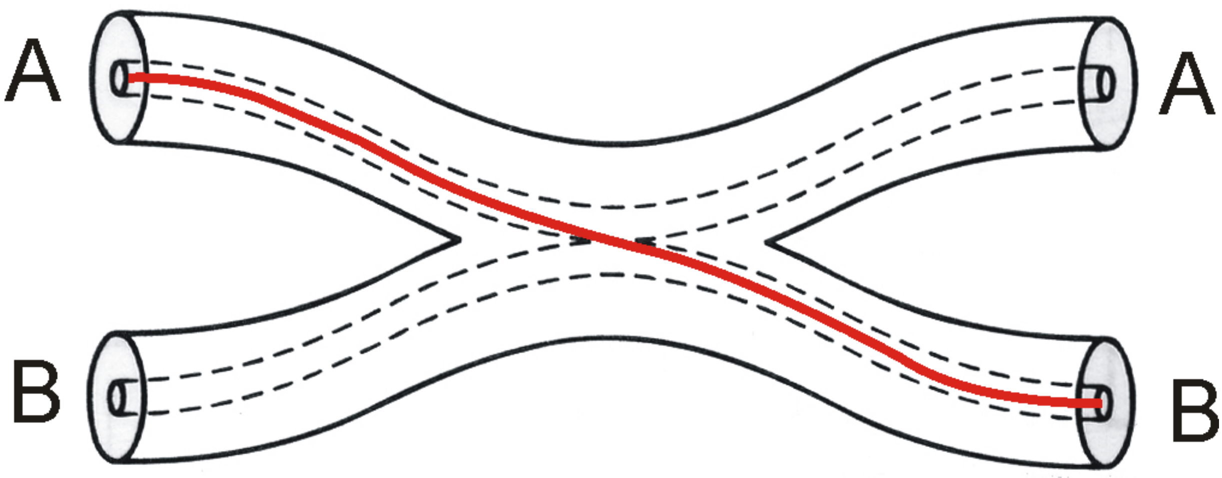

***Fig. 3.4**. The optical splitter.*

Fig. 3.4 shows a splitter that works with single-mode of the fiber. When two splitter are in close contact with each other as shown in Fig. 3.8, there is a resonance phenomenon. Lighting the flow of fiber A is captured core fiber B. Level of power, passed in fiber B is dependent on the taper length. Luminous flux of the fiber A can be fully enters into the fiber B in a certain length. This length varies depending on the wavelength of light in the fiber. The coefficient branching thus can be tuned by selecting a desired of the taper length [15].

3.2.5. Polarization Beam Splitter

The Polarization Beam Combiner/Splitter is a compact high performance lightwave component that combines two orthogonal polarisation signals into one output fiber or to split signal on two orthogonal polarisation signals into two output. Such elements are used to separate polarisation state which corresponded to maximum of pulses intensity. This element is one of the general element for achieving of mode-locking.

Polarisation beam splitters can be based on polarizing cube. A polarizing cube beam splitter consists of a pair of right angle prisms cemented together (Fig. 3.5). The hypotenuse face of one prism is coated with a special multilayer dielectric coating. When non-polarized light is normally incident upon the entrance face, it is separated into two polarized beams, emerging through two adjacent faces in perpendicular directions and polarized orthogonally to each other. The transmitted beam is p-polarized while the reflected beam is s-polarized. When the linearly polarized light is incident, it is similarly divided into two beams in a ratio depending upon the orientation of the electric field vector of the incident light beam. These polarizing beamsplitters are available for many common laser wavelegths and broadband ranges.

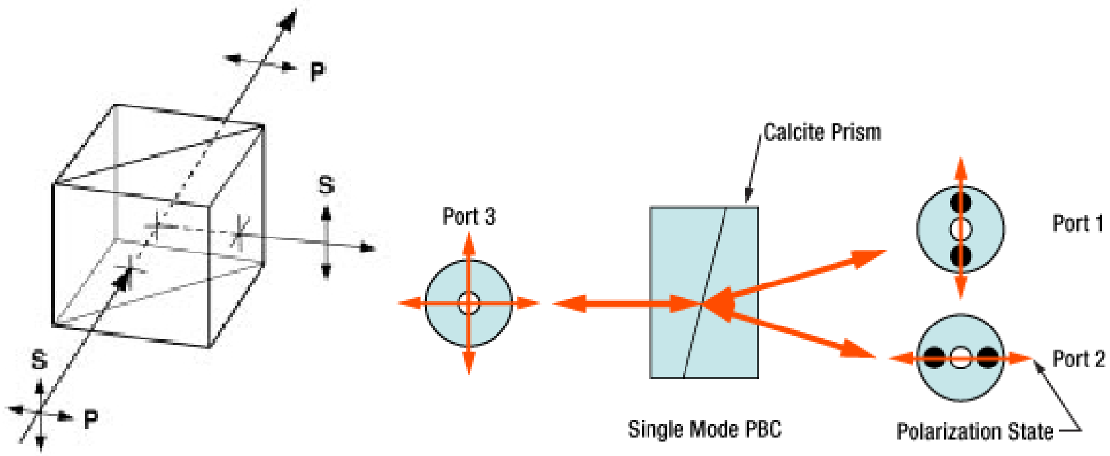

Fig. 3.5. *The polarization beam cube.*

The typical configuration uses the SM fiber for the input and two PM fibers for the output.

3.2.6. Polarization controller

A polarization controller - a device to control the state of polarization of the radiation. A beam of light can be thought of as being composed of two orthogonal electrical vector field components that vary in amplitude and frequency. Polarized light occurs when these two components differ in phase or amplitude. Polarization in optical fiber has been extensively studied and a variety of methods are available to either minimize or exploit the phenomenon

Controlling the polarization state in optical fiber is similar to the free space control using waveplates via phase changes in the two orthogonal states of polarization. In general, two configurations are commonly used in all-fibre lasers [16].

In the first configuration, a Half-Wave Plate (HWP) is sandwiched between two Quarter-Wave Plates (QWP) and the retardation plates are free to rotate around the optical beam with respect to each other. The first QWP converts any arbitrary input polarization into a linear polarization. The HWP then rotates the linear polarization to a desired angle so that the second QWP can translate the linear polarization to any desired polarization state.

An all-fiber controller based on this mechanism can be constructed, with several desirable properties such as the low insertion loss and cost, as shown in Fig. 3.6. In this device, three fiber coils replace the three free-space retardation plates. Coiling the fiber induces stress, producing birefringence inversely proportional to the square of the coils' diameters. Adjusting the diameters and number of turns can create any desired fiber wave plate. Because bending the fiber generally induces insertion loss, the fiber coils must remain relatively large.

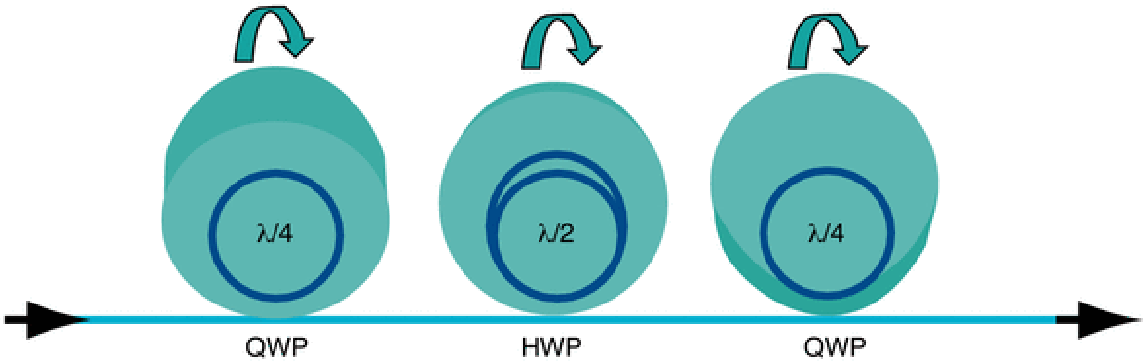

Fig. 3.6. *Polarization control using multiple coiled fiber [16].*

The second approach is based on the Babinet-Soleil Compensator. An all-fiber polarization controller based on this technique is shown in Fig. 2.7 . The device comprises a fiber squeezer that rotates around the optical fiber. Applying a pressure to the fiber produces a linear birefringence, effectively creating a fiber wave plate whose retardation varies with the pressure. Simple squeeze-and-turn operations can generate any desired polarization state from any arbitrary input polarization.

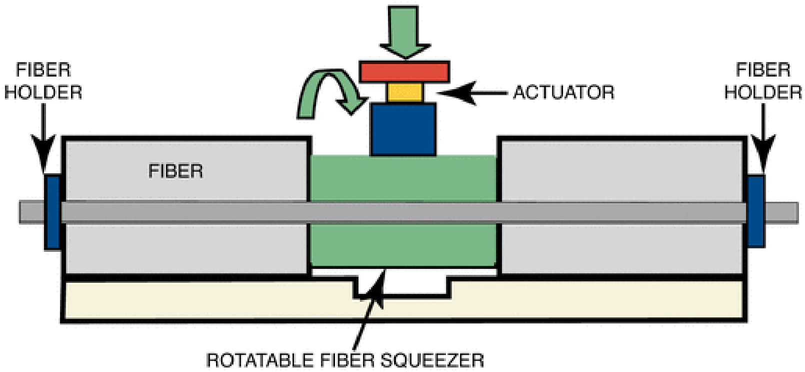

Fig. 3.7. *Polarization control using Babinet-Soleil compensator principle [16].*

3.2.7. Isolator

An optical *isolator* is a two-port passive component that allows light (in a given wavelength range) to pass through with low attenuation in one direction, while isolating (providing a high attenuation for) light propagating in the reverse direction. Isolators are used as both integral and in-line components in laser diode modules and optical amplifiers, and to reduce noise caused by multi-path reflection in highbit-rate and analog transmission systems [13].

An optical signal propagating along the fiber is reflected from various discontinuities in particular locations on a dry joint, formed by optical couplers. As a result of reflection of the energy returned. In the laser cavity induced by the reflected signal can increase, leading to a spurious signal.

The most crucial way to suppress the return flow is based on the use of optical isolators. The optical isolator provides a light transmission in the same direction almost without losses, and in the other (opposite) direction with high damping. Optical isolators are now a key element of many laser systems, optical amplifiers, and are also used as a separate element of an optical link.

At the core of the optical isolator is the Faraday effect - the rotation of the polarization plane of light optically inactive substances under the influence of a longitudinal magnetic field.

An optical isolator consists of three elements: a polarizer 1 (input polarizer), Faraday rotator 2 and analyzer 3 (the output polarizer), Fig. 3.8. Faraday rotator parameters are chosen so that the axis of polarization of the light passing through it unfolded at 45 °. Under the same angle as the axis of the polarizers are set [15].

A **Faraday rotator** is an optical device that rotates the polarization of light due to the Faraday effect, which in turn is based on a magneto-optic effect. The Faraday rotator works because one polarization of the input light is in ferromagnetic resonance with the material which causes its phase velocity to be higher than the other.

The plane of linearly polarized light is rotated when a magnetic field is applied parallel to the propagation direction. The empirical angle of rotation is given by:

$$\beta = VBd$$

where β is the angle of rotation (in radians), B - the magnetic flux density in the direction of propagation (in teslas), d - the length of the path (in metres) where the light and magnetic field interact, V - the Verdet constant for the material.

The Verdet constant (V) varies with wavelength and temperature and is tabulated for various materials.

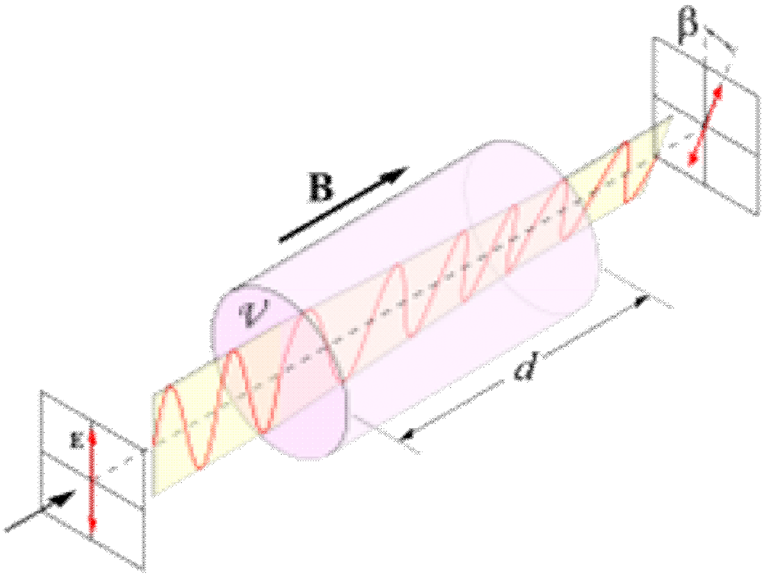

__Fig. 3.8.__ Polarization mechanism due to the Faraday effect. The field lines are usually closed through a permanent magnet around the rotator [13].

The principle of operation of optical isolator

The input signal passing through the polarizer 1, a vertical component leaves unchanged eliminating horizontal component, Fig. 3.9 a. Further vertically polarized light passes through the Faraday Rotator 2, turns the plane of polarization by 45 °, and smoothly passes through the analyzer 3.

When light propagates in the opposite direction it is also polarized in the plane of the analyzer 3 and then passes through Faraday Rotator 2 is horizontally polarized. Thus, the polarization axis of the polarizer 1 and form an angle of 90 °, so the polarizer 1 is not opposite the radiation passes Fig. 3.9 b.

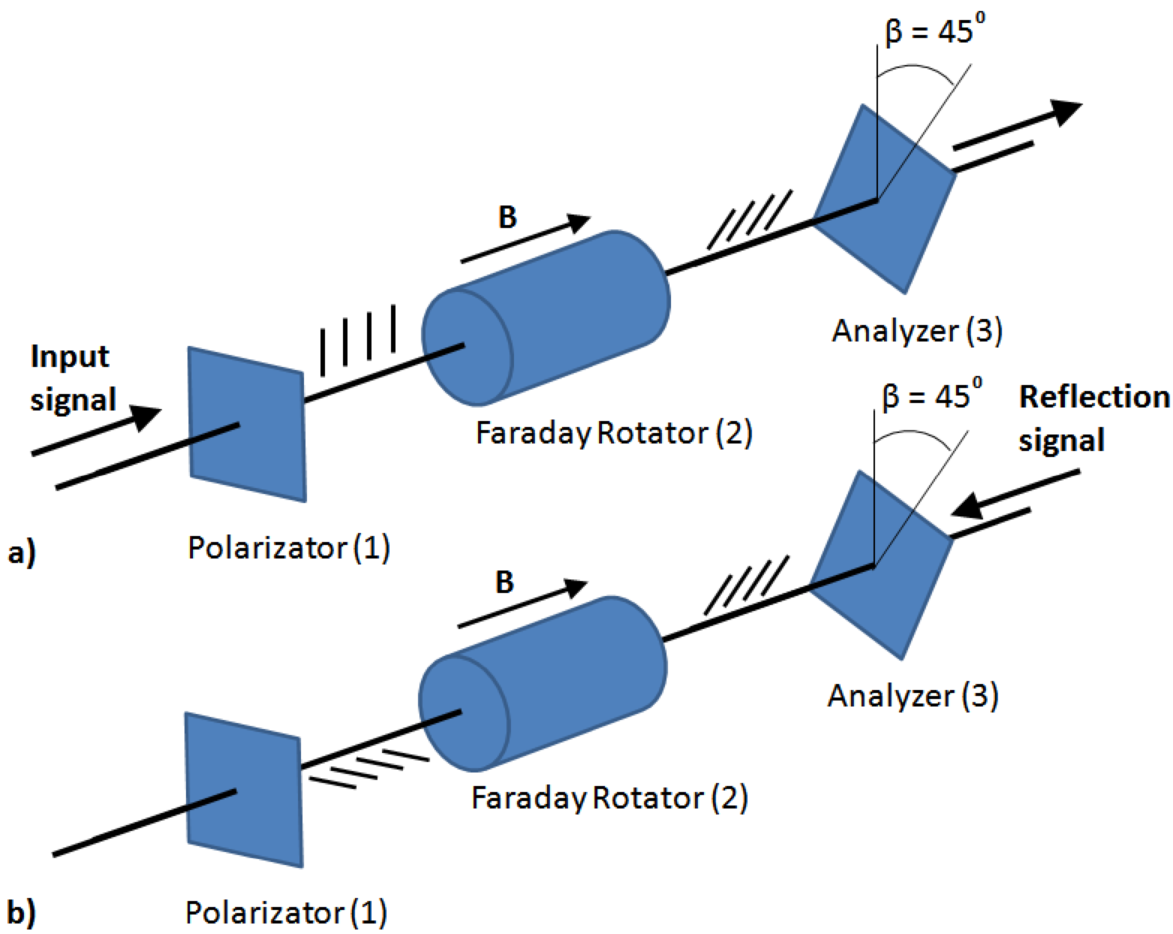

Fig. 3.9. *Scheme of the optical isolator: a) the input signal in the forward direction extends freely, b) the reflection signal in the reverse direction is absorbed polarizer.*

3.2.8. Faraday Mirror

Thermal and mechanical perturbations introduced to a standard, single mode fiber often cause variations in the state of polarization (SOP) of the guided light. These changes can adversely affect the performance of many different types of fiber optic systems. Retaining the SOP using polarization-maintaining (PM) fiber can reduce or eliminate these adverse effects, but PM fiber is costly and often difficult to incorporate effectively. The Faraday Rotator Mirror is a low-cost, passive device that correctly compensates for such SOP variations.

The Faraday mirror consists of a Faraday rotator and a mirror (Fig. 3.10). The Faraday Effect describes the non-reciprocal rotation of a signal's polarization as it passes through an optical medium within a magnetic field. Situated at the end of an optical fiber, the Faraday Rotator Mirror is designed to rotate a signal's SOP by 45°, twice-once when the light enters, and again when the light is reflected back into the fiber. Since the Faraday Effect is non-reciprocal, the resultant SOP is rotated by 90° with respect to the original signal. In this way, any SOP fluctuations that occur anywhere along the fiber are exactly compensated and their unwanted effects neutralized [17].

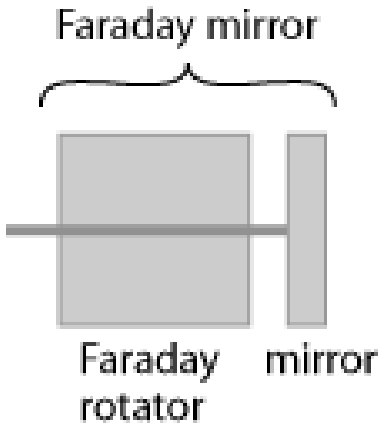

Fig. 3.10. The Faraday mirror.

Reference

1. L. E. Nelson et al., Ultrashort-pulse fiber ring lasers //Appl. Phys. B 65, 277-294 (1997).
2. В.И. Денисов, А.В. Иваненко, И.И. Корель, Б.Н. Нюшков, В.С. Пивцов, Оптоволоконные фемтосекундные лазеры для метрологии и телекоммуникаций // Всероссийская конференция по волоконной оптике 2007 (Пермь), Сборник по материалам конференции.
3. Brian R. Washburn, Scott A. Diddams, Nathan R. Newbury, Jeffrey W. Nicholson, Man F. Yan, Carsten G. Jorgensen, "Phase-locked two-branch erbium-doped fiber laser system for long-term precision measurements of optical frequencies", OPTICS LETTERS, 2004, Vol.29, No.3, C.250-252
4. M. E. Fermann, L.-M. Yang, M. L. Stock, M. J. Andrejco "Environmentally stable Kerr-type mode-locked erbium fiber laser producing 360-fs pulses", OPTICS LETTERS, 1994, Vol. 19, No. 1
5. X. Tian, M. Tang, X. Cheng, P. Shum, Y. Gong, and C. Lin, "High-energy wave-breaking-free pulse from all-fiber mode-locked laser system," Opt. Express 17, 7222-7227 (2009). http://www.opticsinfobase.org/abstract.cfm?uri=oe-17-9-7222
6. M. Zhang , L. Chen, C. Zhou, Y. Cai, L. Ren, Z. Zhang, “Mode-locked ytterbium-doped linear-cavity fiber laser operated at low repetition rate,” Laser Phys. Lett. 6, 657-660 (2009).http://onlinelibrary.wiley.com/doi/10.1002/lapl.200910047/abstract
7. E. J. R. Kelleher, J. C. Travers, E. P. Ippen, Z. Sun, A. C. Ferrari, S. V. Popov, and J. R. Taylor, "Generation and direct measurement of giant chirp in a

passively mode-locked laser," Opt. Lett. 34, 3526-3528 (2009).http://www.opticsinfobase.org/abstract.cfm?uri=ol-34-22-3526

8. E. J. R. Kelleher, J. C. Travers, Z. Sun, A. G. Rozhin, A. C. Ferrari, S. V. Popov and J. R. Taylor, Appl. Phys. Lett. 95, 111108 (2009)

9. S. Kobtsev, S. Kukarin, S. Smirnov, A. Latkin, and S. Turitsyn. Proceedings of the European Conference on Lasers and Electro-Optics (CLEO/Europe-EQEC 2009), Munich, Germany, 2009, CJ8.4

10. X. Tian, M. Tang, P. Shum, Y. Gong, C. Lin, S. Fu, and T. Zhang, "High-energy laser pulse with a submegahertz repetition rate from a passively mode-locked fiber laser," Opt. Lett. 34, 1432-1434 (2009).http://www.opticsinfobase.org/ol/abstract.cfm?uri=ol-34-9-1432

11. J.-H. Lin, D. Wang, and K.-H. Lin, “High energy pulses generation with giant spectrum bandwidth and submegahertz repetition rate from a passively mode-locked Yb-doped fiber laser in all normal dispersion cavity,” Laser Phys. Lett. 8, 66–70 (2011).http://onlinelibrary.wiley.com/doi/10.1002/lapl.201010084/abstract

12. Y. Senoo, N. Nishizawa, Y. Sakakibara, K. Sumimura, E. Itoga, H. Kataura, and K. Itoh, "Ultralow-repetition-rate, high-energy, polarization-maintaining, Er-doped, ultrashort-pulse fiber laser using single-wall-carbon-nanotube saturable absorber," Opt. Express 18, 20673-20680 (2010).

13. https://www.wikipedia.org

14. Е.М. Дианов, В.В. Двойрин, В.М. Машинский, А.А. Умников, М.В. Яшков, А.Н. Гурьянов, Непрерывный висмутовый волоконный лазер// Квантовая Электроника, 2005, Том 35, № 12, с. 1083-1084.

15. Фриман Р., Волоконно-оптические системы связи, Техносфера (2003).

16. http://www.newport.com/Tutorial-Polarization-in-Fiber-Optics/849671/1033/content.aspx
17. http://www.rp-photonics.com

4. Self-mode-locked Er fibre laser with 3.56–km linear-ring cavity.

The development a low-cost long-cavity erbium-fiberfibre laser operating in a stable single-pulse mode-locked regime which provides output pulse energies in excess of 1.0 μJ with a kilohertz-scale repetition rate at a 1.55- μm wavelength is great interested. The lasing wavelength erbium lasers are in the range of telecommunications and are quite in demand for many telecommunications, metrology, biomedical, and lidar applications. In addition, for this wavelength (1.55 μm) is designed a large number of fiber-optic components and the different types of fibers that offer great opportunities to optimize the parameters of the radiation and the creation of cheap sources of pulsed radiation. Pulsed laser radiation with such characteristics (wavelength ~ 1.55 μm, pulse duration < ns, pulse energy ~ 1 μJ and more) is required for many practical applications (e.g. lidar measurements, long-distance atmospheric communications, and biomedicine technologies).

Historically the first mode-locked kilometers-length fibre lasers were ytterbium-based high-energy pulsed fibre lasers whose generation wavelengths lie within 1.0÷1.1μm [1-6]. In such lasers were used conventional telecom fibres for increasing cavity length.

The similar approach being applied to erbium-based mode-locked fibre lasers has not resulted in the similar dramatic increase of pulse energies. The wavelength-depending dispersion properties of optical fibres make pulsed regimes of Er-based fibre lasers differ from those of Yb-based fibre lasers. Conventional low-cost telecommunication single-mode fibres (SMF), that are the most natural candidate for laser cavity elongation, exhibit normal chromatic dispersion at the lasing wavelengths of Yb-fibre lasers, but the anomalous one within the spectral range of Er-fibre lasers (1.5÷1.6 μm). Stable generation of wave-breaking-free high-energy pulses in mode-locked Yb-fibre lasers is enabled by all-normal intracavity dispersion [7-10]. Pulses generated in such lasers are often referred to as dissipative solitons [11, 12]. Their physics does not impose fundamental limitations on the maximum pulse energy, as opposed to soliton-like pulses generated in mode-locked fibre lasers with anomalous intracavity dispersion [7, 13, 14]. In the all implemented types of long-cavity Er-based passively mode-locked lasers constructed from conventional anomalous-dispersion SMF the output pulse energy is limited to values less than 20 nJ [15-17]. Due to the phenomena attributable to non-dissipative solitons, such as energy quantization and decay of high-order solitons [18], any attempts to raise pulse energy above this level bring the lasers into a multiple-pulse regime or turn them to a harmonic mode-locking. To avoid such negative effects and to scale up the pulse energy by analogy with the ytterbium-based lasers the intracavity dispersion in the erbium-based lasers has to be normal as well. Feasibility of passively mode-locked Er-fibre lasers with net-normal cavity dispersion that operate in the dissipative soliton regime has recently been demonstrated in [19-23]. Such lasing regime has allowed reaching a pulse energy level as high as 0.56 μJ in a self-mode-locked Er-fibre laser with a 1.25-km-long cavity [15]. The laser cavity has been elongated by a dispersion compensating fibre module (DCFM), which is normally used in fibre-optics communication lines to compensate for the anomalous dispersion of conventional SMFs. Though such approach has resulted in high-performance lasing, the very high cost of DCFMs, as compared with most SMFs, may be a limiting factor for further cavity scaling up.

A linear-ring all-fibre resonator, successfully tested in our previous work [19], has been used as the base configuration to build the higher-energy mode-locked Er-fibre laser. The specific feature of such a resonator (Fig. 3.1) is given by insertion of an optical-fibre circulator into an originally ring cavity. This circulator diverts the radiation into a long linear arm and also plays the role of an optical diode, thereby enforcing the unidirectional generation mode within the ring part of the cavity. The linear arm is terminated by a Faraday mirror which compensates for linear birefringence in this arm. Thus, an efficient compensation for polarization instability and polarization mode dispersion, which might be accumulated over the long linear arm, is provided. In principle, the ratio between the lengths of the ring and the linear arms of the resonator may be arbitrary. Therefore such a combined resonator might be either predominantly ring or almost linear one.

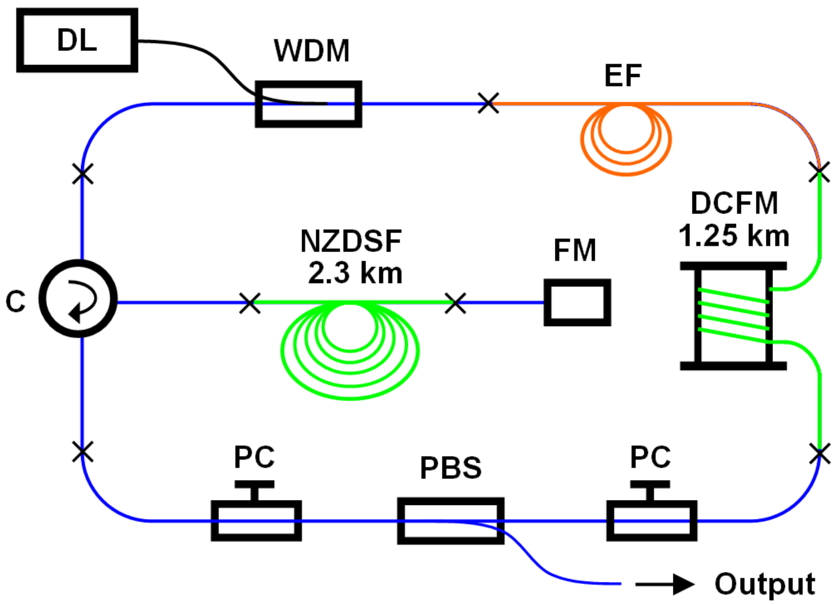

Fig. 3.1. *Schematic of the laser: DL – pumping diode laser; WDM – wavelength-division multiplexer; EF – erbium-doped fibre; DCFM – dispersion compensating fibre*

module; PC – polarization controller; PBS – polarizing beam-splitter; C – circulator; NZDSF – non-zero dispersion-shifted fibre; FM – Faraday mirror.

The active medium of the laser is a 2.2-m-long highly-doped erbium fibre “Liekki Er30-4/125” (absorption 30±3 dB/m at 1,530 nm) which is placed in the ring part of the cavity. The laser is pumped at a wavelength of 980 nm by a fibre-coupled diode laser. The maximum pump power is 450 mW. The pump radiation is injected through a wavelength-division multiplexer.

Self-mode-locking in this laser is achieved by exploiting nonlinear polarization evolution [7, 13]. A fibre-optical polarization beam splitter located in the ring part of the cavity is used as a polarization discriminator and simultaneously as an output coupler.

In the vicinity of 1.55 μm the erbium fibre has a normal chromatic dispersion comparable in magnitude with the dispersion of conventional SMFs. All intracavity SMFs with anomalous dispersion (the pigtails of fibre-optical elements) are no longer than 25 cm each. Their total contribution to the overall group velocity dispersion of the cavity ($\Sigma\beta_2$) has been estimated as only −0.05 ps^2.

Unlike Ref [15], the linear arm of the laser cavity has been elongated by a 2.3-km-long single-mode telecommunication fibre which complies with the ITU-T G.655 standard. This is a so-called non-zero dispersion-shifted fibre (NZDSF). The specified zero-dispersion wavelength of this fibre is 1,598 nm, which is almost at the boundary of the operating spectral range of erbium lasers. At 1.55 μm this fibre exhibits a slightly normal chromatic dispersion ($D \approx -3$ $ps \cdot nm^{-1} \cdot km^{-1}$). Its contribution to the overall group velocity dispersion of the cavity is approximately +17.6 ps^2.

The laser cavity has been also supplemented with a dispersion compensating fibre module “N-DCFM-C-10-FA” made by Sumitomo. This module contains a 1.25-km-long special single-mode fibre with a large normal chromatic dispersion ($\beta_2 \approx +217$ ps^2 at 1.55 μm). Its dispersion curve does not approach zero within operating spectral range of erbium lasers. The optimal location of the DCFM has been found experimentally. The highest energy efficiency of the laser has been reached with the DCFM located in the ring part of the cavity (as shown in Fig. 1). The main reason for that is significant optical loss introduced by the DCFM (up to 1.9 dB per pass).

Thus, the net cavity dispersion has been made a large normal one over the whole spectral band of the laser active medium.

Characteristics of fibres of the mode-locked Er fibre laser with 6-km cavity length are shown in Table 3.1.

Table 3.1. Characteristics of fibres of the mode-locked Er fibre laser with 6-km linear-ring cavity

Name	***Labeling scheme***	***Descriptions and parameters***
Additional fibre in linear part	NZDSF	– Non-zero dispersion-shifted fibre; – Specified zero-dispersion wavelength - 1,598 nm; – $\Sigma\beta_{2\ NZDSF}$ =+17.6 ps^2; – Length - 2.3 km – Attenuation – 0.44 dB per pass
Additional fibre in ring part	DCFM	– Dispersion compensate fibre module; – Sumitomo N-DCFM-C-10-FA; – $\Sigma\beta_{2\ DCFM} \approx +217$ ps^2 at 1.55 µm; – Length: 1.25 km – Attenuation : 1.9 dB per pass
Active fibre	EF	– Erbium-doped fibre; – Liekki Er30-4/125; – absorption 30±3 dB/m at 1,530 nm; – $\Sigma\beta_{2\ EF} = -0.2$ ps^2 – Length: 2.2 m
Passive fibre		– Standard single mode fibre; – $\Sigma\beta_{2\ SMF} = -0.05$ ps^2; – Length: 2.5 m
Total dispersion of the cavity		$\Sigma\beta_2 = \Sigma\beta_{2\ NZDSF} + \Sigma\beta_{2\ DCFM} + \Sigma\beta_{2\ SMF} + \Sigma\beta_{2\ EF} = +17.6\ ps^2 + 217\ ps^2 - 0.05\ ps^2 - 0.2\ ps^2 = 234.4\ ps^2$

Results and discussions.

Mode-locking is self-triggered when the pump power exceeds ~150 mW. Depending on the adjustments of the polarization controllers, ether a multi-pulse operation (harmonic mode-locking) or single-pulse regime (one pulse per resonator period) can be initiated. The shape and duration of pulses also depend on the settings of the polarization controllers. The parameters specified below correspond to the optimal mode-locked lasing regime in which a stable generation of pulses with the fundamental repetition rate, the highest energy, and the shortest duration is sustained.

The laser radiation spectrum registered by an optical spectrum analyzer is shown in Fig. 3.2.

The transform-limited pulse duration is calculated from the formula:

$\Delta\nu \cdot \Delta t_{Gaus} = 0.441$ (3.7.1.4) – for the Gaussian pulse shape,

$$\Delta\nu = \nu_1 - \nu_2 = \frac{c}{n \cdot \lambda_1} - \frac{c}{n \cdot \lambda_2} = \frac{c \cdot (\lambda_2 - \lambda_1)}{n \cdot \lambda_1 \cdot \lambda_2} \simeq c \cdot \frac{\Delta\lambda}{n \cdot \lambda_0^2}$$

where $\Delta\nu$ - the width of the frequency spectrum, ν_1 and ν_2 - frequency at half of the maximum intensity of the frequency spectrum, λ_1 and λ_2 – wavelengths at half of the maximum intensity of the optical spectrum, $\Delta\lambda$ - the width of the optical spectrum, c – the light speed, λ_0 – the central lasing wavelength.

The center wavelength is near 1552 nm, and the spectral width is about 6 nm. It corresponds to a 0.9picoseconds transform-limited pulse width for the Gaussian pulse shape. In spite of that, the actual output pulse duration measured by means of a fast photodiode and a broadband oscilloscope is around 13 ns (Fig. 3.3). Thus it indicates very strong pulse chirping.

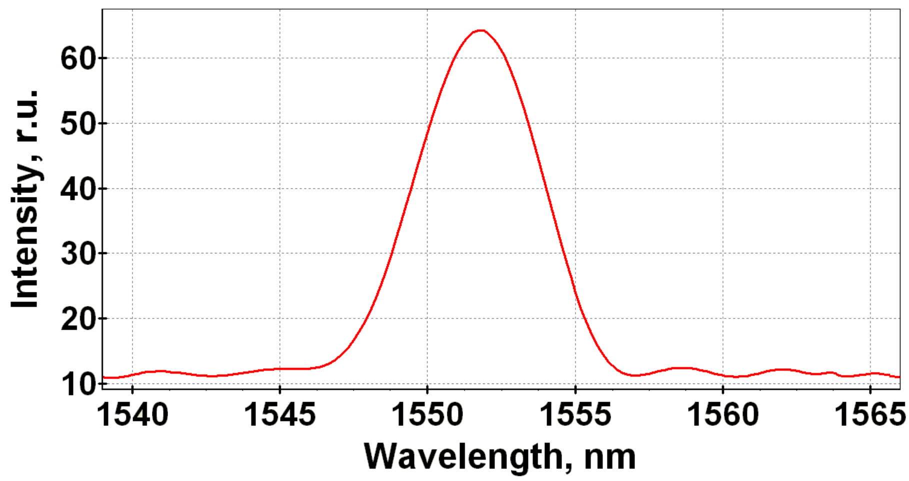

Fig. 3.2. *Optical spectrum of the laser.*

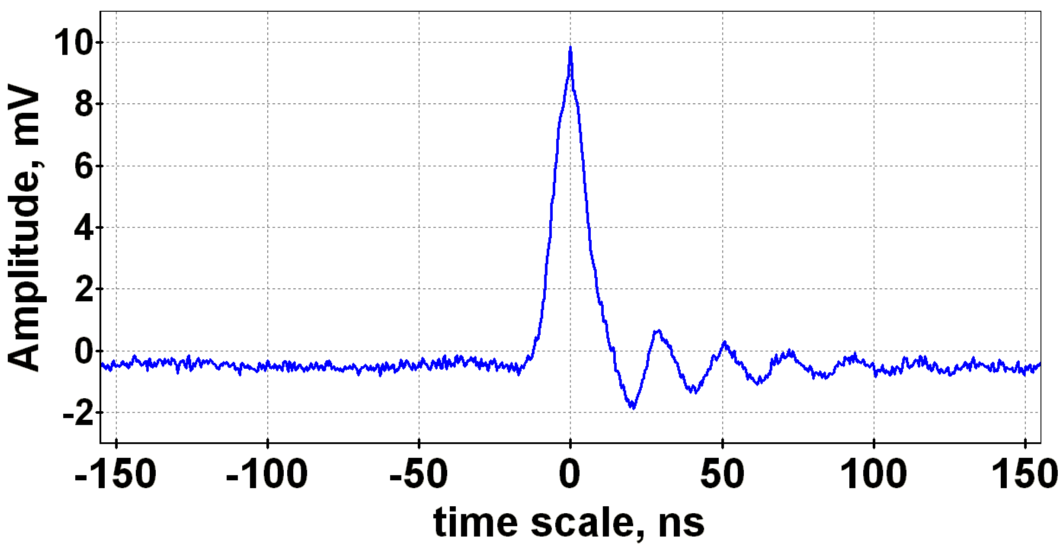

Fig. 3.3. *Oscillogram of a single pulse.*

Shown in Fig. 3.4is an oscilloscope trace of the generated pulse train. The train has a uniform interpulse interval of ~28.5 μs corresponding to the cavity round-trip time.

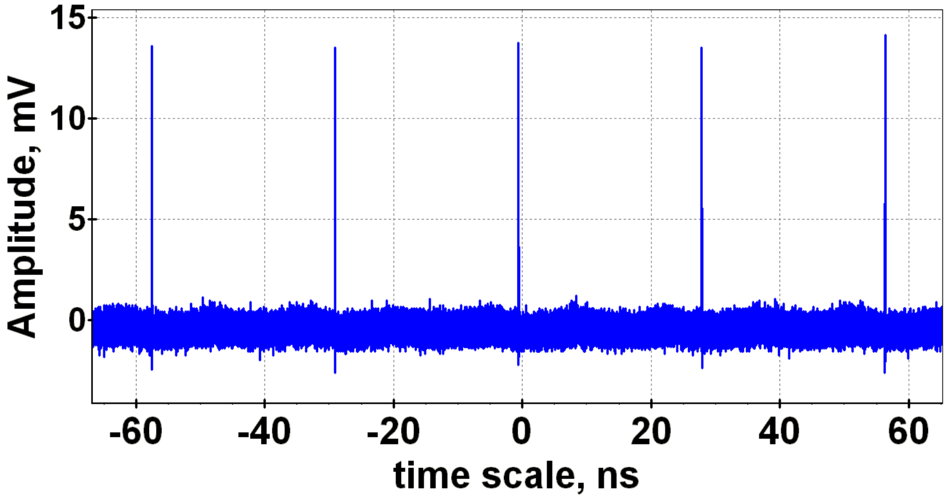

Fig. 3.4. *Oscillogram of a pulse train.*

Examination of intermode beats spectra using a broadband RF spectrum analyzer showed high spectral purity and good frequency stability. Even for high-order beats (at frequencies ~10 MHz) the signal/noise ratio is higher than 45 dB (Fig. 3.5). The measured intermode frequency is ~ 35.1 kHz. It corresponds to the fundamental pulse repetition frequency.

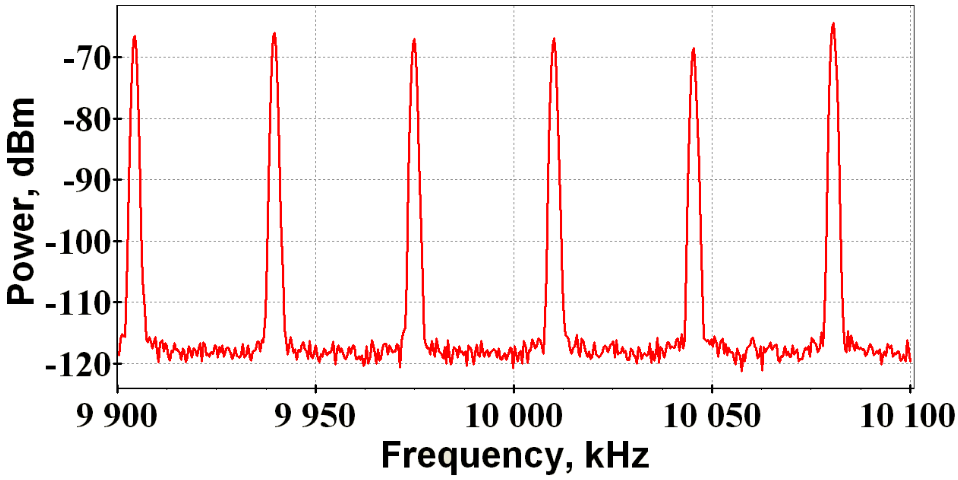

Fig. 3.5. *Intermode beats spectrum.*

The average output power is approximately 22 mW at the triggering pump power (150 mW), and it reaches 58.2 mW at the maximum pump power (450 mW). Thus the maximum output pulse energy can be estimated as 1.66 μJ. The maximum pulse energy, obtained in this laser, was limited by the available pump power.

The described lasing regime is sufficiently stable: under laboratory conditions it was continuously maintained during several hours, despite the absence of any thermal stabilization and vibroacoustic isolation of the laser.

Thus self-mode-locking in the considered laser configuration involving a kilometers-long non-zero dispersion-shifted fibre along with a dispersion compensating fibre module allows reaching pulse energies in excess of 1.0 μJ. The large normal net cavity dispersion enables stable wave-breaking-free lasing, but also leads to very strong pulse chirping. The linear-ring cavity design with compensation for polarization instability in the kilometers-long linear arm facilitates reliable self-mode-locking based on nonlinear polarization evolution.

Summary.

We have demonstrated stable self-mode-locking in an all-fibre erbium-based laser with a kilometers-long net-normal-dispersion cavity. It has resulted in direct generation of short laser pulses with an ultra-low repetition rate of 35.1 kHz and a very high energy of nearly 1.7 μJ at a wavelength of 1.55 μm. Since no output saturation and no wave-breaking effects have been observed at the maximum available pump power (450 mW), a further pulse energy scaling up seems to be possible.

The laser cavity has been fabricated from commercially-available telecom fibres and optical-fibre elements. Its unconventional linear-ring design with compensation for polarization instability ensures high reliability of the self-mode-locking operation, despite the use of non-polarization-maintaining fibres.

Reference

1. A. M.Zheltikov.Ultrashort Pulseand Methods of Nonlinear Optics (Nauka, Moscow, 2006) [in Russian].
2. B. Ibarra-Escamilla, O. Pottiez, E. A. Kuzin, R. Grajales-Coutino, and J. W. Haus, "Experimental investigation of a passively mode-locked fibre laser based on a symmetrical NOLM with highly twisted low birefringence fibre," Laser Phys. **18**, 914–919 (2008).http://www.springerlink.com/content/txq40u0622286221/
3. S. Kobtsev, S. Kukarin, S. Smirnov, A. Latkin, and S. Turitsyn. *Proceedings of the European Conference on Lasers and Electro-Optics (CLEO/Europe-EQEC 2009),* Munich, Germany, 2009, CJ8.4
4. X. Tian, M. Tang, P. Shum, Y. Gong, C. Lin, S. Fu, and T. Zhang, "High-energy laser pulse with a submegahertz repetition rate from a passively mode-locked fibre laser," Opt. Lett. **34**, 1432-1434 (2009).http://www.opticsinfobase.org/ol/abstract.cfm?uri=ol-34-9-1432
5. X. Tian, M. Tang, X. Cheng, P. Shum, Y. Gong, and C. Lin, "High-energy wave-breaking-free pulse from all-fibre mode-locked laser system," Opt. Express **17**, 7222-7227 (2009). http://www.opticsinfobase.org/abstract.cfm?uri=oe-17-9-7222
6. L. Chen, M. Zhang, C. Zhou, Y. Cai, L. Ren, Z. Zhang, "Ultra-low repetition rate linear-cavity erbium-doped fibre laser modelocked with semiconductor saturable absorber mirror," Electronics Lett. **45**, 731-733 (2009).http://scitation.aip.org/getabs/servlet/GetabsServlet?prog=normal&

id=ELLEAK000045000014000731000001&idtype=cvips&gifs=yes&ref=no

7. Haensh T.W. Rev. Mod. Phys., **78** (4), 1297 (2006).
8. B.N. Nyushkov, I.I. Korel, V.I. Denisov, V.S. Pivtsov and N.A. Kolyada, "Sub-nanosecond high-energy pulses from ultra-long mode-locked erbium fibre lasers," Proc. SPIE **7994**, 799406 (2010).http://spiedigitallibrary.org/proceedings/resource/2/psisdg/7994/1/799406_1?isAuthorized=no
9. F.W. Wise, A. Chong, and W.H. Renninger, "High-energy femtosecond fibre lasers based on pulse propagation at normal dispersion," Laser Photon. Rev. **2**, 58–73 (2008).http://onlinelibrary.wiley.com/doi/10.1002/lpor.200710041/abstract
10. N. Akhmediev, J. M. Soto-Crespo, and Ph. Grelu, Phys. Lett. A **372**, 3124–3128 (2008).
11. K. H. Fong, S. Y. Set, and K. Kikuchi, in*Proceedings of IEEE/OSA Optical Fibre Conference (OFC) 2007,*Anaheim, 2007, OTuF2.
12. N. Akhmediev and A. Ankiewicz (eds.), Dissipative Solitons, Lecture Notes in Physics, Springer Series, Vol. 661 (Springer, Berlin/Heidelberg, 2005).
13. O. Pottiez, B. Ibarra-Escamilla, E. A. Kuzin, R. Grajales-Coutino, C.-M. Carrillo-Delgado, Laser Phys. **20**, 709–715 (2010).
14. A. V. Tausenev, P. G. Kryukov, Quantum Electron. **34**, 106–110 (2004).
15. S. Kobtsev, S. Kukarin, and Y. Fedotov, "Ultra-low repetition rate mode-locked fibre laser with high-energy pulses," Opt. Express **16**, 21936-21941 (2008).http://www.opticsinfobase.org/abstract.cfm?URI=oe-16-26-21936

16. E. J. R. Kelleher, J. C. Travers, Z. Sun, A. G. Rozhin, A. C. Ferrari, S. V. Popov and J. R. Taylor, Appl. Phys. Lett. **95**, 111108 (2009)
17. S. M. Kobtsev, S. V. Kukarin, S. V. Smirnov, Y. S. Fedotov, "High-energy mode-locked all-fibre laser with ultralong resonator," Laser Phys. **20**, 351-356 (2010).http://www.springerlink.com/content/g510823212856871/
18. W.H. Renninger, A. Chong, and F.W. Wise, "Dissipative solitons in normal-dispersion fibre lasers," Phys. Rev. A**77**, 023814 (2008).http://pra.aps.org/abstract/PRA/v77/i2/e023814
19. V.I. Denisov, B.N. Nyushkov, V.S. Pivtsov, "High-energy pulses at a very low repetition rate from a self-mode-locked all-fibre erbium laser with large normal cavity dispersion," Proc. SPIE **7580**, 75802U (2010).http://spiedigitallibrary.org/proceedings/resource/2/psisdg/7580/1/75802U_1?isAuthorized=no
20. Z.C. Luo, A.P. Luo, W.C. Xu, C.X. Song, Y.X. Gao, W.C. Chen, Laser Phys. Lett. **6**, 582-585 (2009).
21. A. Cabasse, B. Ortaç, G. Martel, A. Hideur, and J. Limpert, Opt. Express **16**, 19322-19329 (2008).
22. A. Ruehl, V. Kuhn, D. Wandt, and D. Kracht, Opt. Express **16**, 3130-3135 (2008).
23. X. Wu, D. Tang, H. Zhang, and L. Zhao, Opt. Express **17**, 5580-5584 (2009).

4. Mode-locking in 25-km fibre laser

In this part of the thesis is reported about a substantial advance in lengthening cavity of mode-locked fibre lasers by demonstrating a single pulse operation in a fibre laser with a record resonator length of 25 km . To the best of our knowledge this is the longest cavity of a mode-locked laser functioning in a single pulse regime.

The experimental setup based on an all-fibre ring cavity configuration is schematically illustrated in Fig. 4.1.The cavity consists of 1.5 meter of active erbium-doped fibre with the absorption coefficient of $\sim 80 \pm 4$ dB / m @ 1530 nm), a fibre multiplexer, two polarization controllers, two couplers 90/10 and 1/99, 25 km of dispersion compensating fibre with normal dispersion $-10 < D$ [ps/nm/km] <-1 in the wavelength range from 1530 to 1605 nm and fibre-coupled polarization-sensitive isolator acting as a polarizer as well as an isolator, and ensuring unidirectional lasing in the ring. Pump light from a 980-nm laser diode with a maximum output power of 250 mWwas launched through a wavelength-division-multiplexed coupler in the opposite direction to the circulation of light generated around 1551 nm. This configuration ensures that non-absorbed pump radiation does not get into the output coupler. The output power was taken out through a 90/10 fibre coupler placed before 25-km fibre. A stable generation in 25-km long resonator was achieved only with such rather strong out-coupling introducing non-adiabatic evolution of the energy along the cavity. Using only 10% of the radiation power in the feedback we reduced the nonlinear effects (including the nonlinear polarization rotation) in the fibre span and achieved a more sustained mode-locking with simultaneous increase the energy of the out-coupled pulse

Mode locking of the laser with net normal dispersion was achieved by using the effect of non-linear rotation of radiation polarisation. The start of mode-locking and the control over the polarisation was implemented by adjustment of two polarization controllers. The first controller was installed at the input of the isolator. The second controller was placed between multiplexer and 90/10 coupler.

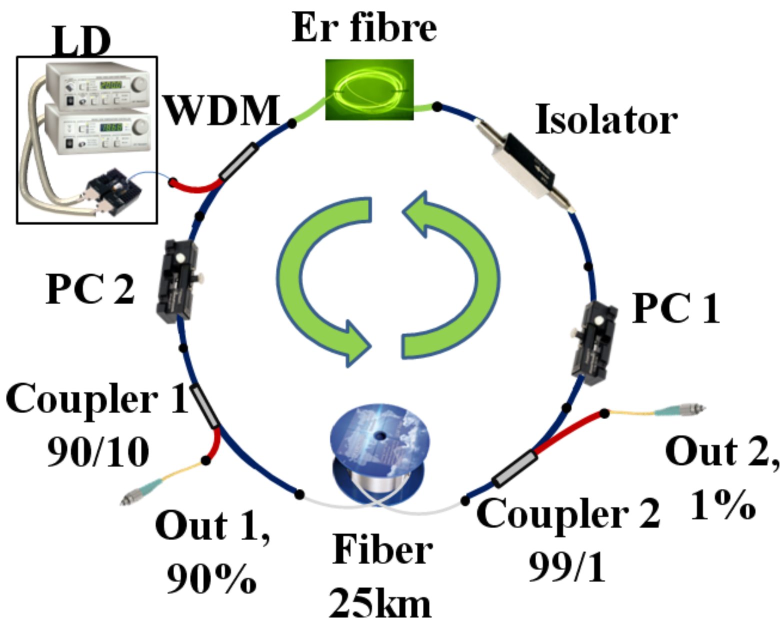

Fig. 4.1. *Schematic depiction of the 25-km long ring fibre laser design.*

Fibres characteristics of the mode-locked Er fibre laser with 25-km cavity length are shown in Table 4.1.

Table 4.1. Characteristics of fibres of the mode-locked Er fibre laser with 25-km cavity length.

Name	***Labeling scheme (Fig.2.1.1)***	***Descriptions and parameters***
Additional fibre in ring part	Fiber 25 km	– Dispersion compensate fibre MetroCore; – -10 < D [ps/nm/km] <-1 in the wavelength range from 1530 to 1605 nm – D = -7.5 at 1551 nm – $\Sigma\beta_{2\ \text{Fiber 25 km}} \approx +239\ ps^2$ at 1.551 μm; – Length - 25 km – Attenuation - <0.25 dB/km
Active fibre	Er fiber	– Erbium-doped fibre; – Liekki Er80-4/125; – absorption ~80 ± 4 dB/m at 1.530 nm; – $\Sigma\beta_{2\ EF} = -0.125\ ps^2$ – Length – 1.5 m
Passive fibre		– Standard single mode fibre; – $\Sigma\beta_{2\ SMF} = -0.12\ ps^2$; – Length – 5 m
Total dispersion of the cavity		– $\Sigma\beta_2 = \Sigma\beta_{2\ NZDSF} + \Sigma\beta_{2\ DCFM} + \Sigma\beta_{2\ SMF} + \Sigma\beta_{2\ EF} = +239\ ps^2 - 0.12\ ps^2 - 0.125\ ps^2 = 238.8\ ps^2$

The second output from the coupler with the split ratio 1/99 was used for monitoring the mode-locked regime with a photodetector–sampling oscilloscope combination with a bandwidth of 1 GHz. **Ошибка! Источник ссылки не найден.** and Fig. 4.3 show the train of the pulses with repetition rate characteristic for the mode-locked regime ($T_R = nL/c$) and a temporal profile of a single pulse with duration of 2,5 ns, respectively. The train of pulses has a period of 123.5 μs which corresponds to a 8.1 kHz repetition rate. As can be seen from the fig. 4.2 fluctuations of pulse intensity in the monitored pulse train did not exceed 10%.

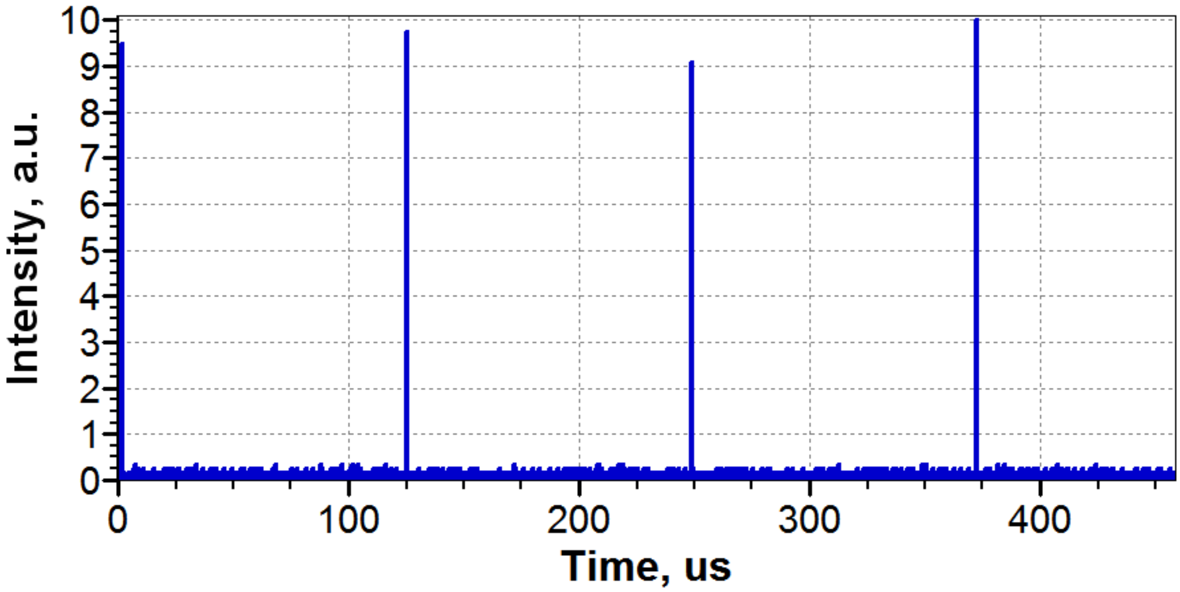

Fig. 4.2. *Schematic depiction of the 25-km long ring fibre laser design.*

The central wavelength of lasing is 1551.2 nm with the width of the optical spectrum in the mode locking regime of 2.2 nm (Fig. 4.4). The temporal duration of bandwidth limited pulse corresponding to the spectrum of 2.2 nm shown in Fig. 4.4 is around 1.4 ps assuming sech^2 pulse shape, therefore, we believe laser operates with highly stretched pulses with large chirp.

For single pulse operation, the average power (output 1) was limited to a maximum of approximately 3 mW corresponding to energy per pulse of 0.37 μJ.

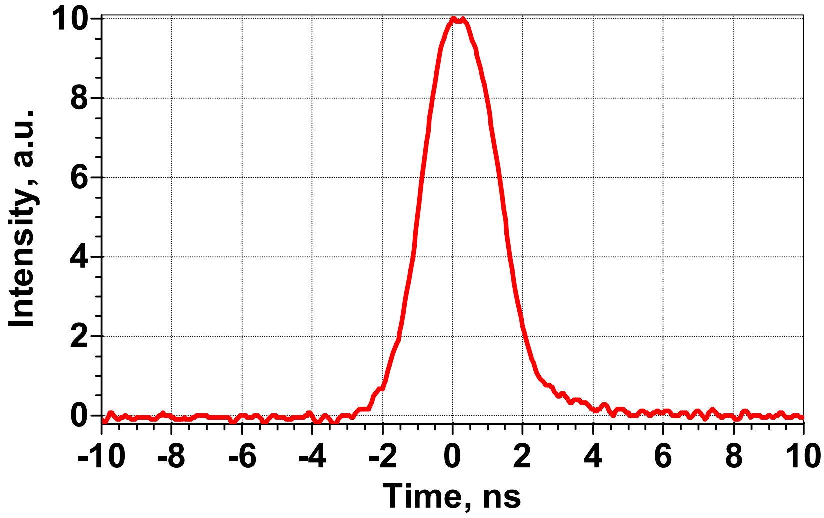

Fig. 4.3. *Temporal profile of the generated pulse measured at the output 1.*

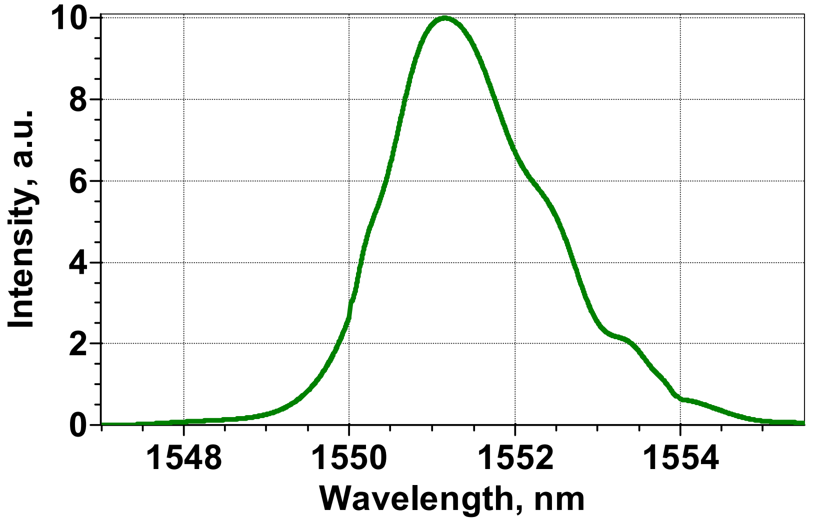

Fig. 4.4. *Spectrum of the generated pulse.*

Results and discussions.

A substantial increase of the cavity length in mode-locked fibre laser leads to the re-scaling of accumulated nonlinear effects and their interplay with dispersion. A systematic investigation and understanding of the underlying physics of such new types of ultra-long mode-locked lasers is still lacking. The presented record cavity length experiment provides new evidence that stable single pulse operation is feasible even with such a sharp increase of the resonator length. We have studied several fibre arrangements for the long mode-locked laser, however, it turned out that single pulse generation regime at such very long cavity lengths is possible only at a balance between the total normal accumulated dispersion, nonlinear effects and loses in the cavity.

With increasing the resonator length and the pulse energy begin to predominate nonlinear processes that lead to the disruption of a single-pulse generation. Intracavity loss leads to lower average power, and accordingly, energy pulses. At the same time, the normal intracavity dispersion leads to a broadening of the pulse duration, which reduces the peak power. The variance is given by the characteristics of the selected fibers and their length.

To reduce the negative impact of non-linear processes request to reduce gain or increase loss in the resonator (or reduce feedback).

In our case, the generation of a single pulse became possible after reducing feedback to 10%. As shown by the experiment, with better feedback cannot achieve the generation of a single pulse, as nonlinear processes lead to multi-pulses regime. Smaller feedback leads to the breakdown of generation, there is only luminescence.

Thus, in such a feedback output pin 90% pulse radiation. Reduced feedback to 10% significantly reduced negative influence of nonlinear processes and at the same time increase the output power of the desired signal.

The dimensionless chirp parameter of the generated pulses can be roughly (assuming Gaussian shape) estimated as a product of the pulse width by the pulse spectral width: $C \approx T_p \times \dfrac{2\pi\, \Delta\lambda\, c}{\lambda_0^2 (1.665)^2} \approx 4351$. This means that the generated pulse is highly-chirped in agreement with the all-normal-dispersion nonlinear dynamics studied recently for mode-locked fibre lasers with standard cavity lengths [19, **Ошибка! Источник ссылки не найден.**, **Ошибка! Источник ссылки не найден.**, **Ошибка! Источник ссылки не найден.**, **Ошибка! Источник ссылки не найден.-Ошибка! Источник ссылки не найден.**]. Note that no special narrow band filter limiting laser radiation spectrum was used in a stable mode-locked operation, unlike the regimes reported in [**Ошибка! Источник ссылки не найден.**, 28].The pulse is never close to transform-limited inside the strictly-normal dispersion fibre cavity and accumulates both large chirp and high energy during propagation down the ultra-long resonator. Evidently, post-compression using an appropriate optical layout or dispersive medium is possible to produce shorter pulses. The accumulation of the chirp in a cavity is compensated by the dissipative laser elements, in our case, by the saturable action of the nonlinear polarisation evolution elements. We anticipate that our work also stimulates investigations and development of new methods for compensation of giant optical chirp that is an inherent feature of the pulses generated in ultra-long mode-locked lasers. The solution of the problem of compression of pulses with giant optical chirp might lead to drastically different architecture of laser systems with high pulse energy and ultra-short pulses.

The energy up-scaling through the increase of the cavity length imposes conditions on the laser system elements. We have observed in a similar class of experiments with slightly shorter cavity length, but higher pumping power, that the important limitation to output power for ultra-long cavity mode-locked fibre lasers is imposed by the optical damage to the end facet of the fibre outputs.The operational mechanism and the physical effects underlying the build-up of radiation and mode-locking in such an unusually long resonator require further investigations. However, our results demonstrate that mode-locking is possible even in the case of very long cavity with length on the scale of tens of km.

Summary.

We have demonstrated single pulse generation regime in all-fibre erbium mode-locking laser based on nonlinear polarization evolution with a record cavity length of 25 km. Mode-locked lasers with such a long cavity have never been studied before. Our result shows a feasibility of stable mode-locked operation even for an ultra-long cavity length.

Simplicity of the examined laser configuration suggests that the proposed scheme has a substantial potential for further improvements. Such a long resonator length opens a possibility to scale up output pulse energy at the same average power of the radiation without use of Q-switching, cavity dumping techniques, or additional optical amplifiers. However, increased peak power and respectively, nonlinear fibre effects make pulse dynamics in such long cavity rather different from standard fibre mode-locked lasers. A possible switching of mode-lock regimes between conventional and rather complex and non-trivial ones with increase of laser cavity length is already demonstrated and discussed in [30].

Reference

1. L.J. Kong, X.S. Xiao, and C.X. Yang, "Low-repetition-rate all-fibre all-normal-dispersion Yb-doped mode-locked fibre laser," Laser Phys. Lett. **7**, 359–362 (2010).http://onlinelibrary.wiley.com/doi/10.1002/lapl.200910162/abstract
2. B.N. Nyushkov, I.I. Korel, V.I. Denisov, V.S. Pivtsov and N.A. Kolyada, "Sub-nanosecond high-energy pulses from ultra-long mode-locked erbium fibre lasers," Proc. SPIE **7994**, 799406 (2010).http://spiedigitallibrary.org/proceedings/resource/2/psisdg/7994/1/799406_1?isAuthorized=no
3. F.W. Wise, A. Chong, and W.H. Renninger, "High-energy femtosecond fibre lasers based on pulse propagation at normal dispersion," Laser Photon. Rev. **2**, 58–73 (2008).http://onlinelibrary.wiley.com/doi/10.1002/lpor.200710041/abstract
4. A. Ruehl, V. Kuhn, D. Wandt, and D. Kracht, Opt. Express **16**, 3130-3135 (2008).
5. A. Chong, J. Buckley, W. Renninger, and F. Wise. Optics Express, **14**, 10095 (2006).
6. L. M. Zhao, D. Y. Tang, and J. Wu, Opt. Lett., **31**, 1788-1790 (2006)
7. V. L. Kalashnikov, E. Podivilov, A. Chernykh, and A. Apolonski. Appl. Phys. **B83**, 503 (2006).
8. A. Chong, W. H. Renninger, and F. W. Wise. J. Opt. Soc. Am. **B25**, 140 (2008);

9. G. Bale, J. N Kutz, A. Chong, W. H. Renninger, and F. W. Wise, J. Opt. Soc. Am. **B 25**, 1763 (2008).
10. N. Akhmediev and A. Ankiewicz (eds.), Dissipative Solitons, Lecture Notes in Physics, Springer Series, Vol. 661 (Springer, Berlin/Heidelberg, 2005).
11. G.P. Agrawal, Nonlinear Fibre Optics, Second ed. (Academic Press, New York, 1995).

5. Gamma-shaped long-cavity normal-dispersion mode-locked Er-fibre laser.

It is well known, that pulse generation regimes in mode-locked fibre lasers are determined by the intra-cavity balance between the effects of dispersion and non-linearity, and the processes of energy attenuation and amplification. In case when the dissipation plays a decisive role in the pulse dynamics, e.g. in fibre lasers with normal intra-cavity dispersion is possible to generate the so-called dissipative optical solitons [1-3]. The dissipative optical solitons can accumulate very high energy without wave-breaking [1, 4, 5].On the other hand, the uncompensated net normal dispersion in long-cavity resonators usually leads to the high chirp [6, 7] and, consequently, to a relatively long duration of generated pulses. Moreover, long-cavity normal-dispersion fibre lasers mode-locked via NPE may tend to a noise-like regime generating double-scale optical peaks [8] with a smooth bell-shaped envelope and stochastic ultra-short pulsed filling, unless a careful adjustment of the laser system parameters is implemented. In all cases the observed duration either of single pulses or double-scale lumps in long-cavity pulsed lasers with normal dispersion varies from few to dozens of nanoseconds.

We have proposed a new design of fibre laser cavity – "γ-configuration", that offers a range of new functionalities for optimization and stabilization of mode-locked lasing regimes. This laser has to operate as a master oscillator in an all-fibre laser system (being also studied in this work) capable of the stable generation of sub-nanosecond high-energy pulses at a kiloHertz-scale repetition rate along with the efficient suppression of amplified spontaneous emission (ASE). Laser systems with such parameters are required in a range of applied problems, in particular, for the generation of high-energy spectral super-continua [9] and for implementation of cutting-edge methods of absorption spectroscopy [10].

The developed laser has an all-fibre linear-ring resonator that is schematically presented in Fig. 5.1. One of the key novel points making the difference from previous designs [5, 11] is that we use an additional linear arm in the resonant cavity. The function of this arm is to sustain mode locking and to control the spectrum of laser radiation. The proposed here cavity design is based on the use a four-port fibre-optics circulator (CIR) that leads to an original "γ-configuration" of the resonator. It offers additional possibilities for optimization of lasing dynamics and control over the radiation parameters in long-cavity normal-dispersion mode-locked fibre lasers. Another important feature of the proposed laser cavity design is a combination of photo-induced in-fibre refractive index gratings: a traditional fibre Bragg grating (FBG) [12, 14]. These elements are used for realization of self-mode-locking and control of the radiation parameters. Such a combination of fibre grating elements has been used for the first time in long-cavity high-energy pulsed lasers.

The functional elements of the laser are distributed along various segments of the resonator in the most optimal way. The ring part of the resonator comprises only of the active Erbium-doped fibre with a pump multiplexor and an output coupler placed before the circulator. Such positioning allows us to achieve the highest possible output power and to suppress non-linear effects in the longest arm of the resonant cavity. The long arm formed by a reel of a single-mode fibre with normal dispersion is ended by a Faraday mirror. This ensures the elimination, or significant suppression, of polarization-induced fluctuations, which could significantly undermine the stability of mode locking upon the use of non-polarization-maintaining fibres. The additional short linear arm contains a combination of the above mentioned TFG and FBG spaced as closely as possible. TFG serves a dual purpose: it works as a polarization discriminator for triggering self-mode-locking through the effect of non-linear evolution of polarization state along the fibre [14, 15] as well as prevents the competition of polarization modes typical for fibre lasers with FBGs [16]. FBG acts as a spectral filter allowing for optimization of the generation dynamics, reducing the pulse duration, and improving the stability of the mode-locked operation. The technique of pulse shaping by intracavity spectral filtering applicable to mode-locked fibre lasers with normal dispersion (see, e.g. [17] and references therein) has not yet been fully explored with regard to the long-cavity lasers. The only notable attempt to use an intracavity spectral filter in a long-cavity high-energy mode-locked fibre laser for stabilization of the lasing wavelength has been just recently reported in Ref. [3]. In the present work we additionally achieve ASE suppression caused by placing a FBG-based bandpass filter into the laser scheme.

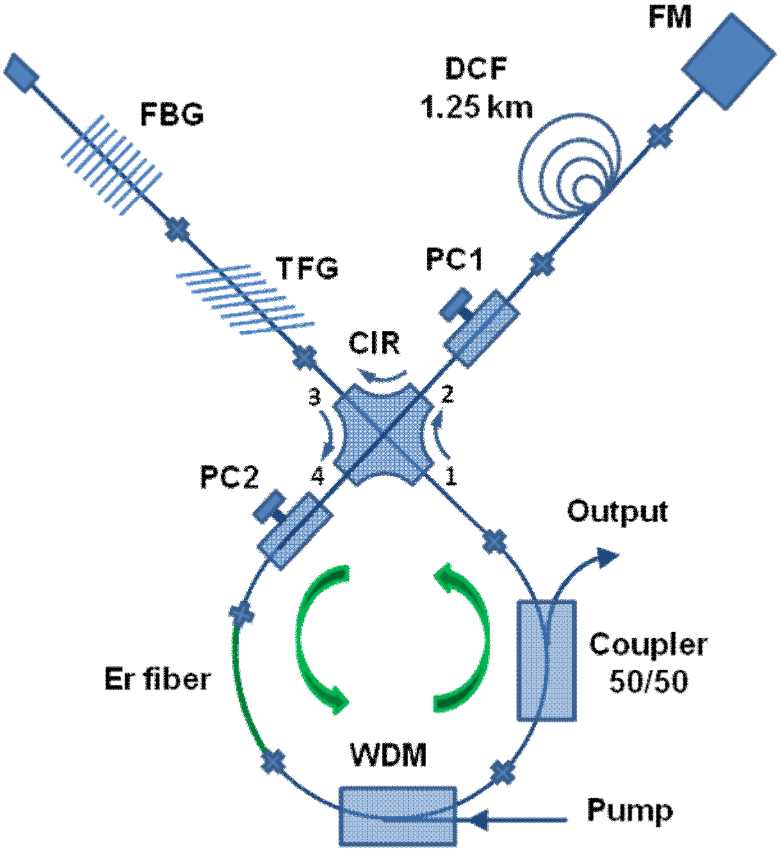

Fig. 5.1. *Schematic depiction of the "γ-shaped" ultra-long cavity ML fibre laser cavity diagram: FBG – fibre Bragg grating, TFG – tilted fibre grating, CIR – circulator, PC – polarization controller, DCF – dispersion compensating fibre, FM – Faraday mirror, WDM – wavelength-division multiplexer.*

The parameters of the fibre-optics elements used in the laser are as follows: Er-fibre — a 1.8-m-long highly-doped fibre with the erbium ion concentration of ~2.1×10^{19} cm^{-3} (Liekki Er30-4/125); DCF — a 1.25-km-long telecom dispersion-compensating fibre with an overall chromatic dispersion of~217 ps^2 and optical losses of ~1.3 dB (Sumitomo N-DCFM-C-10-FA); FBG — an UV inscribed fibre Bragg grating with a peak reflectivity of ~95,55%, the peak wavelength of ~1540.4 nm, and the bandwidth of ~2.61 nm; TFG — an UV inscribed tilted fibre grating with a blaze angle of ~45°, similar to the gratings reported in Ref. [12, 14]; CIR — a four-port polarization-insensitive circulator (Opneti CIR-4-A-1550) ; PC1, PC2 — in-line polarization controllers; WDM — a 980/1550-nm wavelength division multiplexor; Pump — a 980-nm fibre-coupled pump source with the maximal output power of 400 mW; Coupler — fused fibre coupler with the 50/50 coupling ratio.

Anomalous-dispersion fibre pigtails of the fibre-optics elements have been cut to minimal possible lengths of 15–25 cm. Their contribution into the net intra-cavity dispersion in the vicinity of the generation wavelength is negligible and does not exceed –0.07 ps^2. The amount of dispersion introduced by the Erbium fibre is also insignificant and makes approximately –0.15 ps^2. Thus, the total intra-cavity dispersion $\Sigma\beta_2$ with the double-pass connection of DCF taken into account exceeds +433 ps^2.

Optimal parameters for certain elements, for example, the FBG bandwidth and the coupling ratio of the output coupler, were determined experimentally basing on the following criteria: high reliability of mode-locked lasing, the shortest duration and the highest energy of generated pulses, as well as high stability of the laser output parameters.

The laser output parameters were measured by means of an optical spectrum analyzer having a resolution down to 0.02 nm and a high-frequency oscilloscope equipped with an ultra-fast photo-diode providing a temporal resolution within 400 ps. In addition, a broadband RF spectrum analyzer was used along with the same ultra-fast photo-diode in order to study intermode beats.

Fibres characteristics of the mode-locked Er fibre laser with “gamma”-cavity are shown in Table 4.1.

Table 5.1. Characteristics of fibres of the mode-locked Er fibre laser with "gamma"-cavity.

Name	***Labeling scheme (Fig.2.1.1)***	***Descriptions and parameters***
		–
Additional fibre in ring part	DCF	– Dispersion compensate fibre module; – Sumitomo N-DCFM-C-10-FA; – $\Sigma\beta_{2\ DCFM} \approx +217\ ps^2$ at 1.55 μm; – Length - 1.25 km – Attenuation - 1.3 dB per pass
Active fibre	Er fibre	– Erbium -doped fibre; – Liekki Er30-4/125; – absorption 30±3 dB/m at 1,530 nm; – $\Sigma\beta_{2\ EF} = -0.15\ ps^2$ – Length - 1.8 m
Passive fibre		– Standard single mode fibre; – $\Sigma\beta_{2\ SMF} = -0.07\ ps^2$; – Length – 3 m
Total dispersion of the cavity		$\Sigma\beta_2 = \Sigma\beta_{2\ DCFM} + \Sigma\beta_{2\ SMF} + \Sigma\beta_{2\ EF} = 2*217\ ps^2 - 0.07\ ps^2 - 0.15\ ps^2 = +433\ ps^2$

Results and discussion.

Depending on the parameters of the polarization controllers and the pre-set pumping power launched into the laser, both multi-pulse and single-pulse mode-locked operation can be triggered. The settings also affect the form and the duration of the output pulses. Below we present the results of a study of the two most favorable operation modes leading to stable pulse generation at the fundamental repetition frequency. In the first mode of operation, the shortest pulse duration (~1.0 ns) is achieved, with an easily triggered start and high stability. The second operation mode leads to the highest pulse energy. However, it is less stable and with longer pulse duration. The generation dynamics in these two modes exhibits substantial differences. In the first mode, the generation spectrum is considerably narrower than the transmission bandwidth of the intra-cavity FBG-based spectral filter. The effect of this "soft" spectral filtration is in reduction of the ASE level as well as in improvement of the self-mode-locking reliability and stability of the output parameters. In the second mode that is observed at higher pump powers, the generation spectrum becomes noticeably wider than the transmission bandwidth of the intra-cavity filter, *i.e.* so-called "strong" filtration takes place. The generation dynamics of mode-locked fibre lasers with normal dispersion and "strong" spectral filtering has been theoretically studied in [18]. Such filtering makes it possible to restrain pulse elongation when the pulse energy is increased. Theoretically, this type of lasing dynamics has been studied for particular laser configurations in [18-20].

***Mode* № 1: the shortest pulse duration with high stability.**

In general, a hysteresis dependence of the operation mode parameters on the pump power is typical for the considered laser system. When a certain level of pumping power is reached (much higher than the lasing threshold), multi-pulse partially mode-locked operation is self-triggered. In this lasing regime quasi-regular trains of nanosecond pulses are generated. Furthermore, at pump powers exceeding 200-250 mW, such trains contain noise-like pulses with an irregular shape of the envelope and stochastic structure. Gradual reduction of the pumping power leads to a corresponding decrease of the number of pulses in the train down to the single-pulse lasing regime (with only one pulse circulating in the cavity). The series of oscillograms in Fig. 5.2 illustrates such transition from multi-pulse lasing to the single-pulse operation mode as the launched pump power is reduced from 400 mW to 40 mW. Duration of the resulting pulse is ~ 1.0 ns, as appears from the high-resolution oscillogram in Fig. 5.3*a*. The pulse train emitted from the laser operating in this mode is regular, with the pulse interval equal to the cavity round-trip time (~12.25 μs) as shown in the insert of Fig. 5.3*a*. The pulse repetition rate corresponds to the fundamental repetition frequency of ~81.6 kHz that is determined by the cavity round trip time. Examination of intermode beats spectra using a broadband RF spectrum analyzer has shown high spectral purity and good frequency stability. Even for high-order beats (at frequencies ~1 MHz) the signal/noise ratio is higher than 45 dB (see the RF-spectrum in Fig. 5.3*b*). The measured intermode frequency is equal to the pulse repetition rate. Thus, the acquired data indicate strong mode locking in the laser set to operate in the described single-pulse regime. This operation mode (hereinafter "operation mode № 1") is very stable with respect to any environmental perturbations and fluctuations of the pump power; it can be continuously maintained throughout a day.

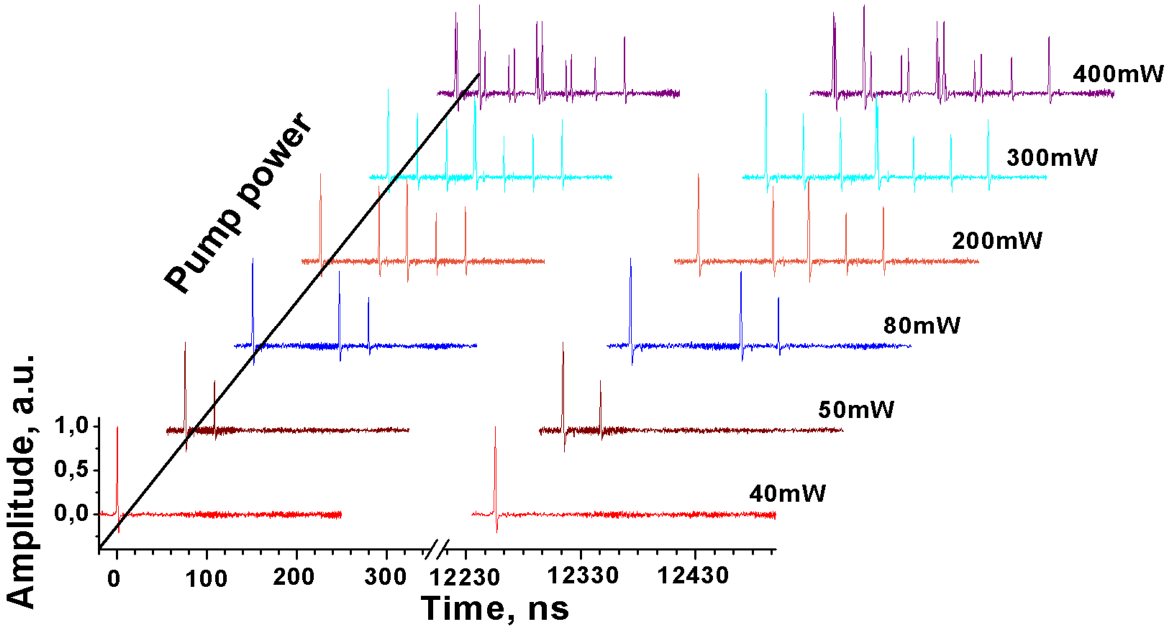

Fig. 5.2. *Series of oscillograms acquired from the laser output to illustrate evolution of the laser operation mode (from multi- to single-pulse lasing) with the change of the pump power. The cavity round trip time is ~12 250 ns.*

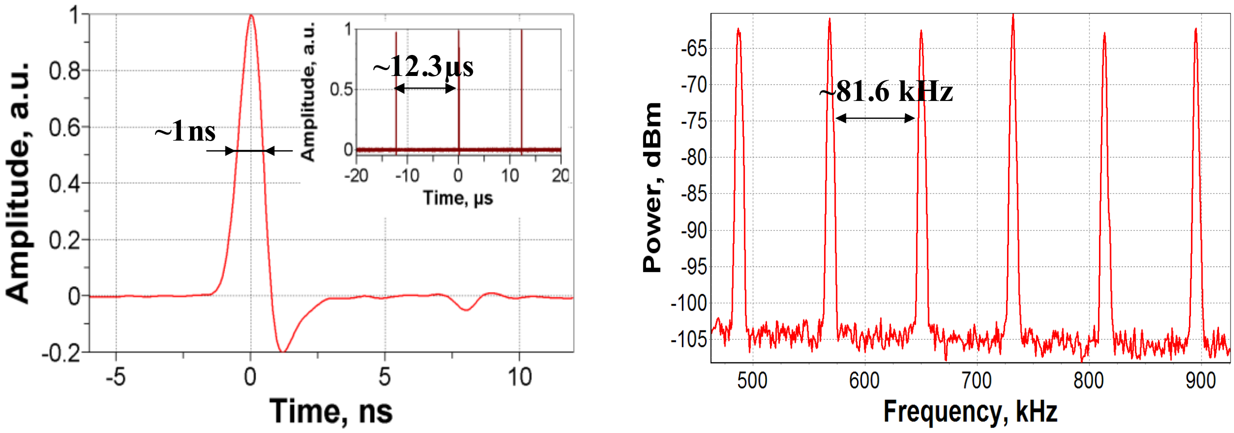

Fig. 5.3. ***a*** *— oscillograms of the laser output during the single-pulse mode-locked operation (mode № 1): the red line – high resolution trace of a single pulse; the brown line (inset) – trace of the regular pulse train.*

b *— intermode beats spectrum acquired during the single-pulse mode-locked operation (mode № 1);*

The character of the evolution of the laser optical spectrum (Fig. 5.4) during the transition from the multi-pulse lasing to the single-pulse operation mode № 1 is in partial agreement with the spectrum variation demonstrated in Ref. [21] that occurs when the pump power is changing. However, the mechanism of emergence of the noise-like pulses at high pump powers in our laser is most probably different than the "peak power clamping effect" pointed out in Ref. [21]. In our case pulse trains occur at a repetition frequency different from the fundamental one and are not always uniformly distributed over the cavity perimeter. The major factor leading to the occurrence of such irregular pulses is likely to be related to wave breaking that takes place when the peak power exceeds a certain threshold. This might be also closely linked to the wave collapse mechanisms proposed and studied in [22, 23]. Another physical mechanism giving rise to wave breaking in ultra-long lasers may be perturbations caused by a strong ASE.

The characteristic sharp edges of the optical spectrum shows the generation of a single pulse at the base by analogy with short laser (Fig. 5.5).

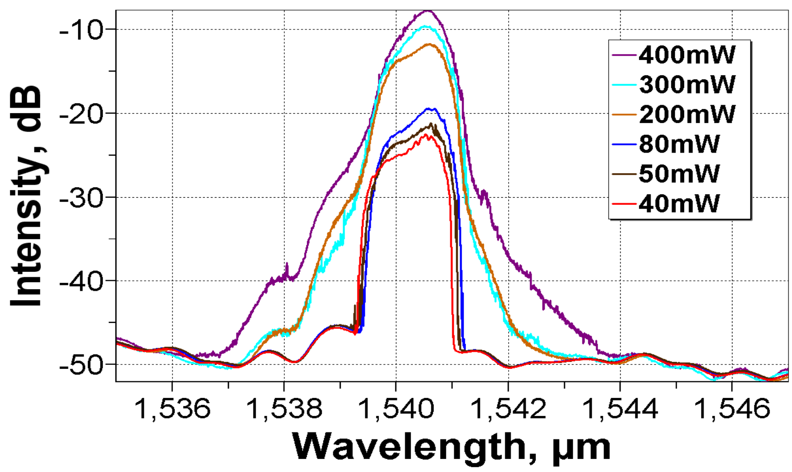

Fig. 5.4. *Laser radiation optical spectra acquired atdifferent pumping power levels.*

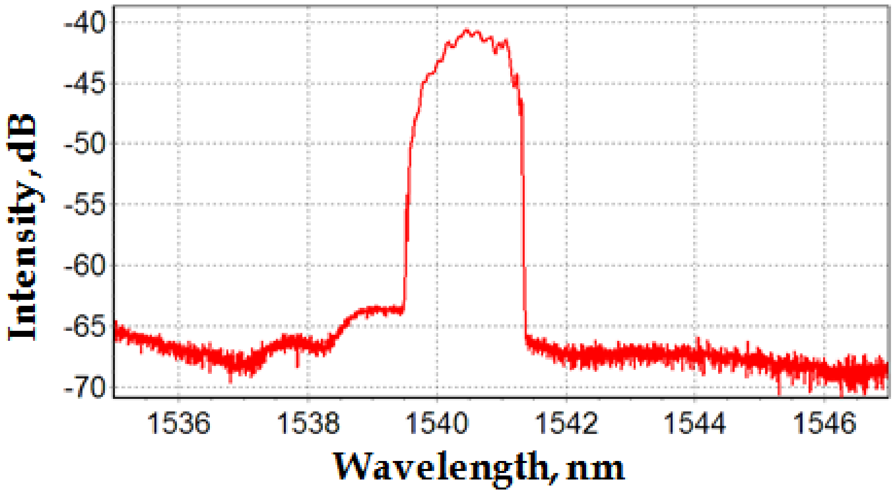

Fig. 5.5. *The optical spectrum of the first mode-locking.*

Despite the moderate average output power (~1.5 mW) of the laser in the operation mode №1, the very low pulse repetition rate allows presumably for accumulation of sufficiently high energy in the generated pulses. However, a realistic estimate of the pulse energy requires consideration of ASE contribution to the laser output.

Indeed, in long-cavity mode-locked fibre lasers, a considerable fraction of the pump energy may be converted into ASE, because of a significant cavity round-trip time and long pulse-to-pulse intervals. For example, in the long-cavity Erbium laser [23], the energy fraction of ASE was as high as 10% to 50% depending on the pulse repetition rate. In our case, the addition of an FBG-based spectral filter has resulted in a substantial reduction of ASE in the laser, which is most noticeable at high pumping powers. Energy contribution of ASE into the output radiation has been estimated by integration of the power spectral density in the single-pulse mode-locked output, in the continuous wave mode, and in the

ASE-source mode (with the FBG being disconnected), all at the same level of the pumping power.

Output spectra in these modes of operation are presented in Fig. 5.6 (the average radiation power at the input of the spectrum analyzer is the same in all cases). Thus, in the studied single-pulse operation mode № 1, the energy proportion of ASE in the output radiation does not exceed, according to our estimate, 5%. A realistic estimate then of the output pulse energy taking into account the ASE factor yields a value of ~17.5 nJ.

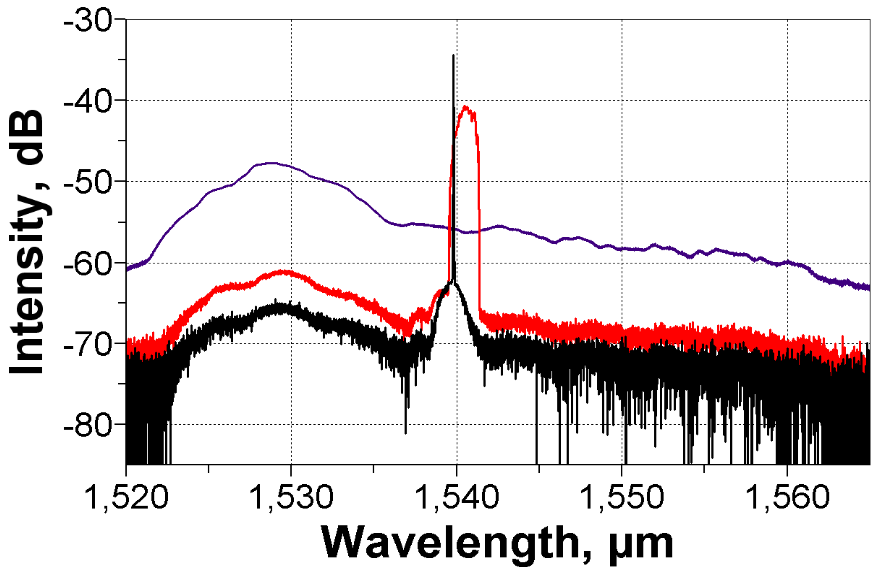

Fig. 5.6. *Optical spectra of the laser radiation: the red line corresponds to the single-pulse mode-locked output (operation mode № 1); the black line — to the CW operation mode; the lilac line — to the ASE-source mode (FBG).*

The effect of intra-cavity spectral filtering on the ASE suppression is noticeable even at low pump levels. As seen in Fig. 5.7, a comparison of the laser radiation spectrum normally acquired from the output coupler and the spectrum acquired from the FBG confirms this conclusion in the case of single-pulse operation mode № 1. One can see that the spectral power density of ASE components registered at the extracavity pigtail of the FBG is higher than that at the exit port of the output coupler.

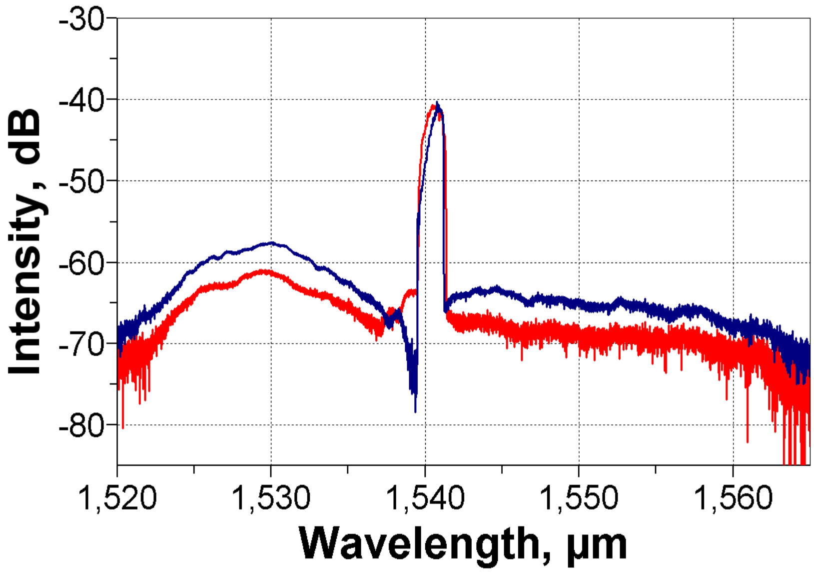

Fig. 5.7. *Optical spectra of the laser radiation during the single-pulse operation mode № 1: the red line corresponds to the spectrum normally acquired from the output coupler; the blue line — to the spectrum acquired from the FBG.*

Mode № 2: the highest pulse energy.

Single-pulse mode-locked operation with the “strong” intracavity spectral filtering is initiated at the maximal pumping power through re-tuning of the both polarization controllers. In this mode, pulses with duration of approximately 2 ns are generated (see the oscillogram in Fig. 5.8). Their optical spectrum that is wider than the transmission band of the intra-cavity filter. A comparison of the laser radiation spectrum normally acquired from the output coupler and the spectrum acquired from the FBG stresses the effect of spectral profiling (see Fig. 5.9). The FBG-based bandpass filter not only cuts away the ASE components in the radiation spectrum, but also narrows the pulse spectrum itself, which gets broadened again due to non-linear effects during a subsequent resonator trip.

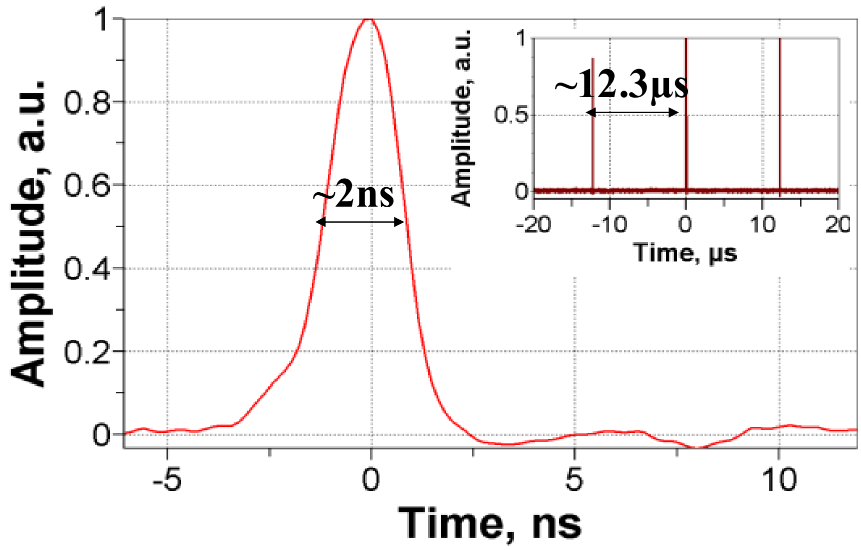

Fig. 5.8. *Oscillograms of the laser output during the single-pulse operation mode № 2: the red line – high resolution trace of a single pulse; the brown line (inset) – trace of the regular pulse train*

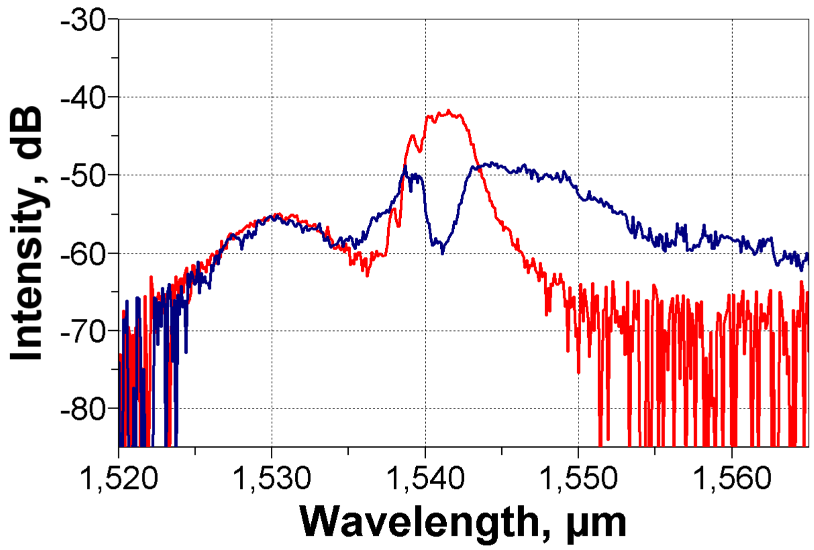

Fig. 5.9. *Optical spectra of the laser radiation during the single-pulse operation mode № 2: the red line corresponds to the spectrum normally acquired from the output coupler; the blue line — to the spectrum acquired from the FBG.*

The average output power in the described operation mode (hereinafter “operation mode № 2”) reaches approximately 8 mW, with the ASE contribution not exceeding 15%. Correspondingly, the pulse energy may reach ~83.3 nJ. This mode is less stable than the first single-pulse operation mode and the output pulses are subject to decomposition under strong environmental perturbations or fluctuations of the pumping power. Most likely, wave breaking of these pulses having a sufficiently high peak power is catalyzed by a high level of ASE noise. Therefore the operation mode № 2 does not last a long time. In a few minutes (typically) the laser turns to a multi-pulse partially mode-locked lasing regime. The laser output has finally an intensity temporal distribution similar to the oscilloscope traces on top of Fig. 5.2 (the traces acquired at high pump power levels).

Basing on the above results, we have chosen the first single-pulse operation mode, as being the most stable, low-noise, and short-pulsed, to work on the “master-oscillator-power-amplifier” system described in the following section.

Amplification and compression.

For further augmentation of the pulse energy, an Erbium-doped fibre amplifier (EDFA) with a double-pass configuration was used as shown in Fig. 5.10. The double pass of laser radiation through the EDFA was arranged by means of a conventional three-port circulator and a Faraday mirror (which is finally replaced by a FBG). The circulator serves both as a unidirectional input and a unidirectional output providing, thus, due optical isolation of the amplifying stage. In order to achieve high gain and to minimize non-linear effects, we make use of a heavily doped erbium fibre (Liekki Er80-8/125) which features a large effective mode area and a very high erbium concentration (~4.7×10^{19} cm^{-3}). The length of this fibre is ~1.5 m. It is core-pumped at both ends by means of 1480-nm fibre-coupled laser diodes delivering ~350 mW each one.

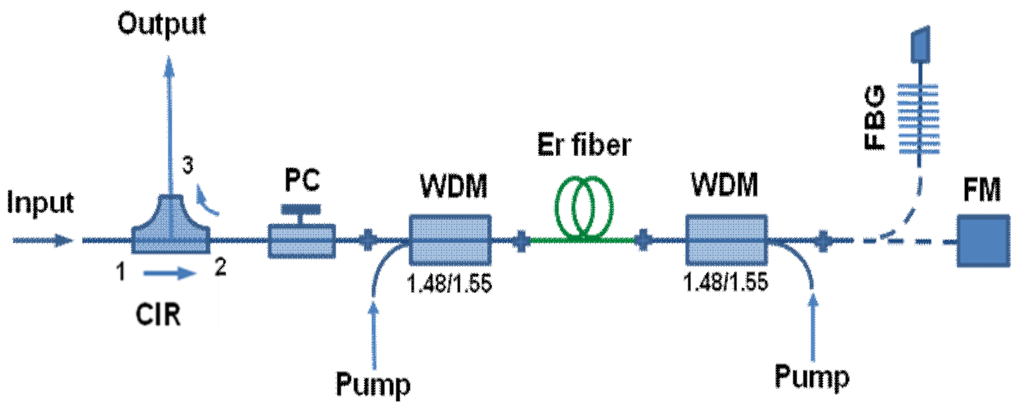

Fig. 5.10. *Diagram of the double-pass EDFA: CIR – circulator, PC – polarization controller, WDM - wavelength-division multiplexer, FBG – fibre Bragg grating, FM – Faraday mirror.*

When a Faraday mirror was used, the average radiation power measured at the amplifier output reached ~116 mW. However, the spectrum diagram of the amplified laser radiation (Fig. 5.11) makes it obvious that the most of this power was distributed into ASE components (up to 71%). Taking this proportion into account, it was estimated that the real energy in the output pulses after amplification did not exceed ~412 nJ. It is interesting to note that the above-mentioned spectrum contains practically no short-wavelength ASE components. This may be explained by a sharply limited (from the short-wavelength side) transmission bandwidth of the multiplexors (WDM) used the EDFA for injection of the pump radiation.

In order to reduce the total level of ASE, the Faraday mirror was replaced by an FBG (similar to the grating used in the laser itself). Performing the function of a band-pass filter, the FBG ensures efficient suppression of long-wavelength ASE components, as evidenced by the radiation spectrum acquired from the amplifier output (Fig. 5.12). When the FBG is used, the average output power reaches ~40 mW, the energy proportion of ASE amounts to less than 3%, and the improved gain allows generation of pulses with energy of ~480 nJ.

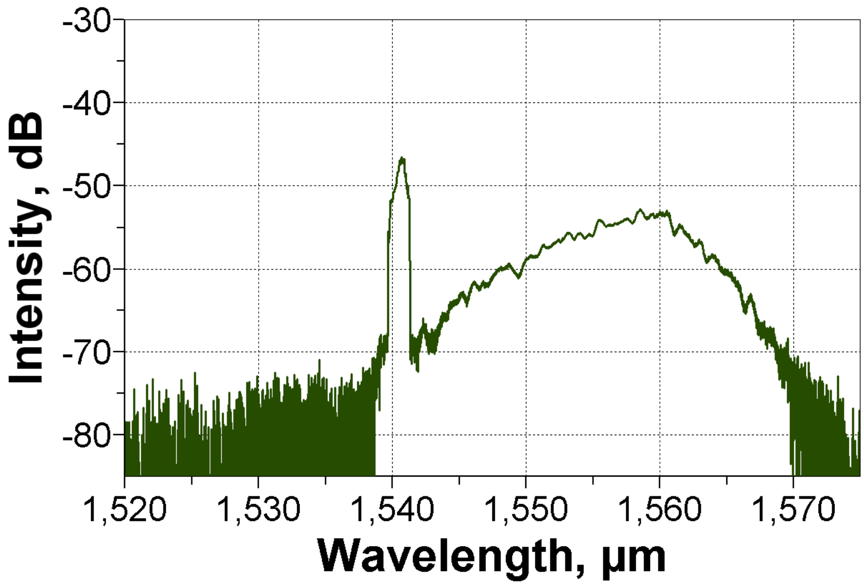

Fig. 5.11. *Optical spectrum of the laser radiation upon amplification in the double-pass EDFA with a Faraday mirror.*

In order to reduce the total level of ASE, the Faraday mirror was replaced by an FBG (similar to the grating used in the laser itself). Performing the function of a band-pass filter, the FBG ensures efficient suppression of long-wavelength ASE components, as evidenced by the radiation spectrum acquired

from the amplifier output (Fig. 5.12). When the FBG is used, the average output power reaches ~40 mW, the energy proportion of ASE amounts to less than 3%, and the improved gain allows generation of pulses with energy of ~480 nJ.

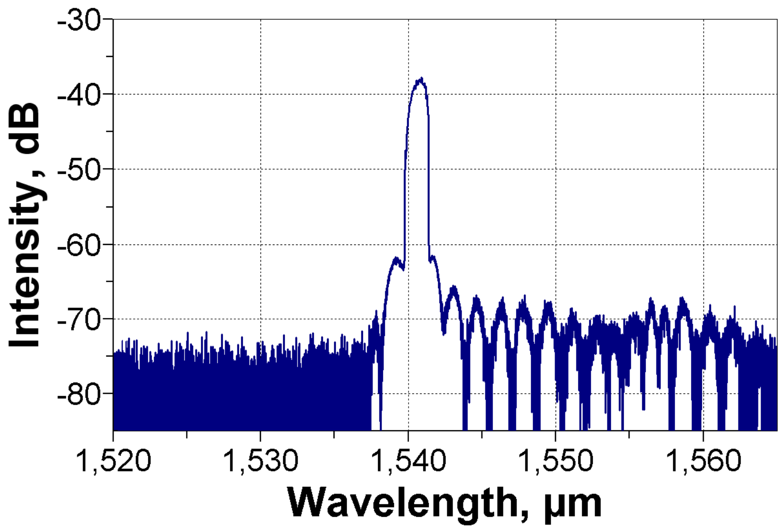

Fig. 5.12. *Optical spectrum of the laser radiation upon amplification in the double-pass EDFA with an FBG.*

After amplification, the pulse duration turns out to be somewhat shorter than before: the oscillograms in Fig. 5.13 demonstrate that 1-ns laser pulses shorten to 0.9-ns pulses upon amplification. The cause of this shortening may be attributed both to dispersive compression coming from the anomalous dispersion of the active fibre and to the spectral filtering by optical elements with limited bandwidth that clips the wings of strongly chirped laser pulses.

It is important to note that a rough estimate of the time-bandwidth product of pulses emitted by the laser yields a figure of more than 100 that may evidence giant chirp in the laser pulses. The net normal dispersion of the laser cavity ensures the positive sign of the chirp.

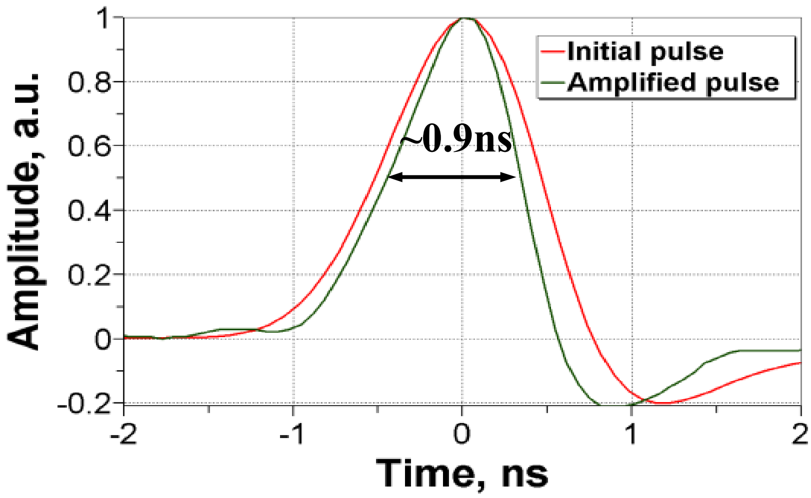

Fig. 5.13. *Oscillograms of laser pulses before (red) and after (dark green) amplification.*

Taking into account the fact that the dispersion of the active fibre used in the EDFA (~16 ps/nm·km @ 1540 nm) is comparable to that of conventional telecommunication fibres which comply with G.652 standard, we also investigated the possibility and efficiency of in-fibre dispersive compression of the laser pulses by using such a telecom fibre.

We have examined the compression of pulses using a single-mode fibre Sumitomo Pure Access. This fibre has anomalous chromatic dispersion of about 17 ps/nm·km (the slope of the dispersion curve is ~ 0.09 ps/nm^2·km) at the laser wavelength. The following results were obtained: substantial shortening of the laser pulses only occurs upon propagation through very long (kilometer-scale) sections of the fibre. Even for a moderate compression comparable to the pulse shortening in the amplifier, a 1-ns pulse emitted by the laser has to travel about 4 km along the above-named passive single-mode fibre with anomalous dispersion. Oscillograms in Fig. 5.14 illustrate the pulse compression effects resulted from propagation over the different lengths of the Sumitomo Pure Access fibre. The pulses were finally compressed down to 0.6 ns in a 25.5-km-long section of this fibre.

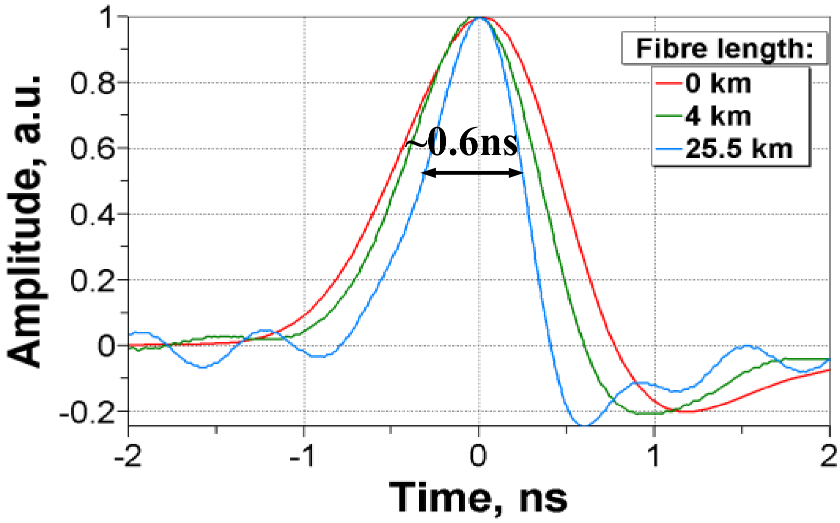

Fig. 5.14. Oscillograms of laser pulses before (red) and after (green and blue) propagation over different lengths of the anomalous-dispersion passive fibre.

Insignificant pulse shortening that we observed in the anomalous-dispersion passive fibre cannot be fully attributed to conventional linear dispersive compression. One of the possible reasons for low compressibility may be a complex structure of the laser pulses [8] or significant nonlinearity of their chirp. Nevertheless the obtained experimental results promise the possibility of more substantial compression of such pulses in sufficiently long single-mode telecommunication fibres of standard G.652. The price of such compression would be a loss of the radiation energy due to optical fibre losses.

Summary.

We have proposed a new design of fibre laser cavity – “γ-configuration”, that offers a range of new functionalities for optimization and stabilization of mode-locked lasing regimes. This novel cavity configuration has been successfully implemented into a long-cavity normal-dispersion self-mode-locked Er-fibre laser. The conducted experimental study has shown that the new cavity design allows for efficient compensation or elimination of most destructive factors that affect lasing dynamics and output parameters of such lasers. In particular, it features compensation for polarization instability, suppression of ASE, reduction of pulse duration, prevention of in-cavity wave breaking, and stabilization of the lasing wavelength. This laser along with a specially designed double-pass EDFA have allowed us to demonstrate an environmentally stable all-fibre laser system able to deliver sub-nanosecond high-energy pulses with low level of ASE noise. The combination of high pulse energy and short pulse duration extends the range of practical applications of long-cavity mode-locked fibre lasers with normal dispersion.

Reference

1. N. Akhmediev and A. Ankiewicz (eds.), Dissipative Solitons, Lecture Notes in Physics, Springer Series, Vol. 661 (Springer, Berlin/Heidelberg, 2005).
2. W.H. Renninger, A. Chong, and F.W. Wise, “Dissipative solitons in normal-dispersion fibre lasers,” Phys. Rev. A**77**, 023814 (2008).http://pra.aps.org/abstract/PRA/v77/i2/e023814
3. K. H. Fong, S. Y. Set, and K. Kikuchi, in*Proceedings of IEEE/OSA Optical Fibre Conference (OFC) 2007,*Anaheim, 2007, OTuF2.
4. N. J. Kutz, SIAM Review, **48,** 629 (2006)
5. V. Denisov, B. Nyushkov, V. Pivtsov, "Self-mode-locked all-fibre erbium laser with a low repetition rate and high pulse energy," Quantum Electron. **40**, 25-27 (2010).http://iopscience.iop.org/1063-7818/40/1/A05
6. M. Zhang , L. Chen, C. Zhou, Y. Cai, L. Ren, Z. Zhang, “Mode-locked ytterbium-doped linear-cavity fibre laser operated at low repetition rate,” Laser Phys. Lett. **6**, 657-660 (2009).http://onlinelibrary.wiley.com/doi/10.1002/lapl.200910047/abstract
7. E. J. R. Kelleher, J. C. Travers, E. P. Ippen, Z. Sun, A. C. Ferrari, S. V. Popov, and J. R. Taylor, "Generation and direct measurement of giant chirp in a passively mode-locked laser," Opt. Lett. **34**, 3526-3528 (2009).http://www.opticsinfobase.org/abstract.cfm?uri=ol-34-22-3526
8. G.P. Agrawal, Nonlinear Fibre Optics, Second ed. (Academic Press, New York, 1995).

9. S.V.Smirnov et al., Mode-Locked Fibre Lasers with High-Energy Pulses. Chapter 3 in book "Laser Systems for Applications", edited by: Dr. K.Jakubczak, pp. 39-58. ISBN 978-953-307-429-0, InTech, 2011
10. S.M.Kobtsev, S.V.Kukarin, S.V.Smirnov, “All-fibre high-energy supercontinuum pulse generator,” Laser Physics **20**, 375-378 (2010).http://www.springerlink.com/content/lx3572743m1g7v75/
11. V.I. Denisov, B.N. Nyushkov, V.S. Pivtsov, “High-energy pulses at a very low repetition rate from a self-mode-locked all-fibre erbium laser with large normal cavity dispersion,” Proc. SPIE **7580**, 75802U (2010).http://spiedigitallibrary.org/proceedings/resource/2/psisdg/7580/1/75802U_1?isAuthorized=no
12. David M. Brown, Kebin Shi, Zhiwen Liu, and C. Russell Philbrick, “Long-path supercontinuum absorption spectroscopy for measurement of atmospheric constituents”, Opt. Express **16**, 8457-8471 (2008).http://www.opticsinfobase.org/abstract.cfm?uri=oe-16-12-8457
13. T. Erdogan, “Fibre grating spectra,” J. of Lightwave Tech. **15**, 1277-1294 (1997).
14. C. Mou, K. Zhou, L. Zhang, and I. Bennion, "Characterization of 45°-tilted fibre grating and its polarization function in fibre ring laser," J. Opt. Soc. Am. B **26**, 1905-1911 (2009).http://www.opticsinfobase.org/abstract.cfm?uri=josab-26-10-1905
15. Haensh T.W. Rev. Mod. Phys., **78** (4), 1297 (2006).
16. H. Inaba, Y. Akimoto, K. Tamura, E. Yoshida, T. Komukai and M. Nakazawa, “Experimental observation of mode behavior in erbium-doped optical fibre ring laser,” Opt. Comm. **180**, 121-125 (2000).

17. B.N. Nyushkov, I.I. Korel, V.I. Denisov, V.S. Pivtsov and N.A. Kolyada, "Sub-nanosecond high-energy pulses from ultra-long mode-locked erbium fibre lasers," Proc. SPIE **7994**, 799406 (2010).http://spiedigitallibrary.org/proceedings/resource/2/psisdg/7994/1/799406_1?isAuthorized=no

18. C. Mou, H. Wang, B. G. Bale, K. Zhou, L. Zhang, and I. Bennion, "All-fibre passively mode-locked femtosecond laser using a 45º-tilted fibre grating polarization element," Opt. Express **18**, 18906 – 18911 (2010).http://www.opticsinfobase.org/abstract.cfm?uri=oe-18-18-18906

19. Brandon G. Bale, and Stefan Wabnitz, "Strong spectral filtering for a mode-locked similariton fibre laser", Opt. Let., vol.**35**, pp. 2466-2468, 2010.http://www.opticsinfobase.org/abstract.cfm?uri=ol-35-14-2466

20. Brandon G. Bale, J. Nathan Kutz, Andy Chong, William H. Renninger, and Frank W. Wise, "Spectral filtering for high-energy mode-locking in normal dispersion fibre lasers," J. Opt. Soc. Am. B 25, 1763-1770 (2008).http://www.opticsinfobase.org/abstract.cfm?uri=josab-25-10-1763

21. Brandon G. Bale, J. Nathan Kutz, "Spectral Filtering Highly Chirped Pulses in All-Normal Dispersion Fibre Lasers", Proceedings of the World Congress on Engineering 2009 Vol. **I**, WCE 2009, July 1 - 3, 2009, London, U.K.

22. L. M. Zhao, D. Y. Tang, J. Wu, X. Q. Fu, and S. C. Wen, "Noise-like pulse in a gain-guided soliton fibre laser", Opt. Express, vol. 15, pp.2145-2150 (2007).

23. A. I. Chernykh and S. K. Turitsyn, "Soliton and collapse regimes of pulse generation in passively mode-locking laser systems", Optics Letters, **20(4)**, 398 (1995)

24. B.N. Nyushkov, V.I. Denisov, S.M. Kobtsev, V.S. Pivtsov, N.A. Kolyada, A.V. Ivanenko, and S.K. Turitsyn, “Generation of 1.7-uJ pulses at 1.55um by a self-modelocked all-fibre laser with a kilometers-long linear-ring cavity,” Laser Phys. Lett. **7**, 661-665 (2010).http://onlinelibrary.wiley.com/doi/10.1002/lapl.201010037/abstract

6. Conclusion

The development and research of novel types of ultra-long cavity mode-locked fibre lasers are important challenges to the creation of high-energy laser light sources with unique parameters for a range of applications in industry, bio-medicine, metrology and telecommunications.

Ultra-long mode-locked fibre lasers might find new applications in recently proposed concept of fully classical reliable key distribution systems [1, 2]. Extension of the boundaries of operation of mode-locked lasers might also lead to new applications in measurements and sensing. Another interesting direction of research is investigation of dispersion-managed dissipative soliton regimes [3-5] in such ultra-long mode-locked lasers.

However, these lasers because of the enormous length of the cavity are very critical to the start mode locking, as well as to external disturbances. The pulse generation in such lasers is due to the balance between the non-linear processes, the dispersion pulse broadening and intracavity loss and gain. Therefore, the development of such lasers must be carefully selecting of the resonator parameters, such as the dispersion length resonator feedback gain.

In addition, such lasers can be generated stochastic pulse packets - nanosecond or picosecond package filled sub-picosecond pulses [6]. Such packages are no longer pulses have a large linear chirp, and therefore cannot be compressed to ultrashort pulses. Thus, it imposes additional criteria to set up ultra-long fibre lasers. If ultra-short pulses exactly are need then precise and accurate adjustment of the polarization controllers requires.

Another problem common to all fibre laser mode-locked by the NPE, including short lasers, is the problem of polarization controllers. Such controllers based upon mechanical deformation of optical fibre [7, 8] (the fibre-coil or rotatable fibre squeezer approach) cannot, as a rule, retain their set parameters for long periods because of plastic deformations in the optical fibre made of amorphous fused silica. Free-space discrete wave plates or waveguide electro-optic crystals may also be used as polarisation controllers with the caveat that there must be at least three such elements in order to cover all possible polarisation states: one half-wave phase element and two quarter-wave ones. These elements have long-term stability, but the adjustment of such controllers is more difficult. In addition to this, these controllers provide additional losses significant additional losses associated with the input of radiation the fibre after the break.

Nevertheless, ultra-long fibre lasers allow simple (only by connecting additional fibres into the cavity) and relatively cheap to obtain pulse generation with a relatively low repetition rate and with a sufficiently large power and energy pulse.

Our results indicate that the physical mechanisms underlying the operation of such lasers involve non-trivial nonlinear interactions of the resonator modes and are quite different from those in other types of lasers. Characterisation of pulses with giant chirp is an interesting emerging experimental area and recent pioneering work [2] shows that post-compression of ns-scale fibre laser pulses with very large chirp is feasible. And the development of new schemes will improve the stability of generation, as well as to optimize the parameters of laser radiation.

This thesis presents the results of research Er-doped ultra-long (more than 1 km cavity length) fibre lasers mode-locked based on NPE.

1. We have developed self-mode-locked erbium-based 3.5-km-long all-fiber laser with the 1.7 μJ pulse energy at a wavelength of 1.55 μm. It has resulted in direct generation of short laser pulses with an ultra-low repetition rate of 35.1 kHz. The laser cavity has netnormal-dispersion and has been fabricated from commercially-available telecom fibers and optical-fiber elements. Its unconventional linear-ring design with compensation for polarization instability ensures high reliability of the self-mode-locking operation, despite the use of nonpolarization-maintaining fibers.

2. We have demonstrated single pulse generation regime in all-fibre erbium mode-locking laser based on NPE with a record cavity length of 25 km. Mode-locked lasers with such a long cavity have never been studied before. Our result shows a feasibility of stable mode-locked operation even for an ultra-long cavity length.

3. We have proposed a new design of fibre laser cavity – "γ-configuration", that offers a range of new functionalities for optimization and stabilization of mode-locked lasing regimes. This novel cavity configuration has been successfully implemented into a long-cavity normal-dispersion self-mode-locked Er-fibre laser. In particular, it features compensation for polarization instability, suppression of ASE, reduction of pulse duration, prevention of in-cavity wave breaking, and stabilization of the lasing wavelength. This laser along with a specially designed double-pass EDFA have allowed us to demonstrate an environmentally stable all-fibre laser system able to deliver sub-nanosecond high-energy pulses with low level of ASE noise.

We hope that further development of ultra-long fibre lasers will create new high energy laser light sources with unique features for new and improved technologies in the field of photonics, biomedical, metrology and telecommunications.

Reference

1. J. M. Soto-Crespo, N. N. Akhmediev, V. V. Afanasjev and S. Wabnitz, Phys. Rev. E 55, 4783 (1997),
2. M. Zhang , L. Chen, C. Zhou, Y. Cai, L. Ren, Z. Zhang, “Mode-locked ytterbium-doped linear-cavity fibre laser operated at low repetition rate,” Laser Phys. Lett. 6, 657-660 (2009).http://onlinelibrary.wiley.com/doi/10.1002/lapl.200910047/abstract
3. J. Scheuer, A. Yariv. Physical Review Letters 97, 140502 (2006).
4. A. Zadok, J. Scheuer, J. Sendowski, A. Yariv. Opt. Express 16, 16680 (2008).
5. B. G. Bale, S. Boscolo, and S. K. Turitsyn, Opt. Lett., 34, 1193 (2009).
6. S.Smirnov, S.Kobtsev, S.Kukarin, and A.Ivanenko. Three key regimes of single pulse generation per round trip of all-normal-dispersion fiber lasers mode-locked with nonlinear polarization rotation. Optics Express, Vol. 20, Issue 24, pp. 27447-27453 (2012).
7. N. Imoto, N. Yoshizawa, J. Sakai, H. Tsuchiya, “Birefringence in single-mode optical fiber due to elliiptical core deformation and stress anisotropy,” IEEE J. Quantum Electronics 16, 1267-1271 (1980).

8. E. Collett, Polarization Controllers, (Polarized Light In Fiber Optics, The PolaWave Group, 2003), Chapter 9.