Mode-Locking in 25-km Fibre Laser

A. Ivanenko[1,2] **S. K. Turitsyn**[1], **S. M. Kobtsev**[2] **and M. Dubov**[1]
[1]*Photonics Research Group, Aston University, Birmingham, B4 7ET, UK*
[2] *Laser System Laboratory, Novosibirsk State University, Novosibirsk, 630090, Russia*

Abstract We demonstrate passive mode-locking and single pulse generation in a fibre laser with a record-setting cavity length of 25 km. Substantial increase in the pulse round trip duration leads to ultra-low repetition rate of 8.097 kHz and the pulse energy of 3.7 μJ.

PACS numbers: 42.55.Wd, 42.60.Fc, 42.60.Da, 42.60.By

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. In particular, laser designs based on new physical concepts offer opportunities for creating systems with non-incremental changes of performance characteristics leading to disruptive progress. In this work we outline a new direction in development of pulsed lasers, by demonstrating a dramatic increase of the cavity length for mode-locking fibre lasers to a record 25 km which corresponds to the cavity optical length of 37.05 km. Our result provides insight in design possibilities which may allow for non-incremental progress in laser technology by pulse energy up-scaling using very long cavities.

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. For a range of laser applications in material processing a high pulse energy or respectively high peak intensity is required. Different techniques such as Q-switching, cavity dumping and optical amplification are currently used to generate high energy pulses. One of the important physical and technical challenges in laser science is to achieve *high pulse energy in mode-locked lasers* to provide tools for a variety of applications ranging from material processing to advanced bio-medical imaging. 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.

Drastic increase of the laser cavity can be implemented using a fibre waveguide. 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 [1]. 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 [2] and with fibre [3, 4] 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 [5, 6] 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 [7-12]. 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 [6].

Generation of stable high-intensity pulses in fibre lasers is achieved through non-trivial nonlinear equilibrium between effects of nonlinearity and dispersion and dissipative mechanisms. In the case of anomalous cavity dispersion the soliton mechanism of balancing dispersion and nonlinearity can be used. However, intensity is limited by the soliton conditions and too high intensity of radiation leads to the generation of multiple solitons and their non-regular interactions in the presence of noise. Recently it was revealed that the mode locking of fibre lasers can also be achieved in the normal dispersion regime [13-20]. The recently discovered all normal dispersion generation regime is based on the interplay of the cavity dispersion, the Kerr nonlinearity and the gain. The importance of spectral filtering for stability of single pulse generation was stressed in [18, 19]. Long-cavity passively mode locked fibre lasers offer advantages in high per-pulse energy, while relative simplicity and reliability. However, increase of the fibre cavity length and corresponding growth of peak power of radiation gives rise to the enhancement of nonlinear effects in the laser resonator. This leads to the aggravation of nonlinear distortions, such as e.g. pulse breaking, multi-pulse generation regimes, random pulsations and other detrimental effects. Long resonator length makes generation in the mode-locked regime much more sensitive to environmental perturbations and nonlinear instabilities in comparison with CW generation. Another critical issue is that this revolutionary raising of energy of short pulses in very long cavity imposes very demanding requirements on resistance to radiation damage of cavity elements. Therefore, substantial increase of the cavity length in fibre mode-locked laser is a significant fundamental and experimental challenge. A number of technical and physical problems should be resolved to create a road map for high pulse energy ultra-low mode-locked laser systems. The first important step is to study how long a cavity of mode-locked fibre laser can be extended in the regime of single pulse generation.

Here we report on 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 optical length of 37.05 km. To the best of our knowledge this is the longest cavity of a mode-locked laser functioning in a single pulse regime. This endeavor opens new prospects for potential up-scaling pulse energy characteristics of mode-locked fibre lasers operating without using optical amplifiers, Q-switched technique or cavity dumping. Exploration of the physical mechanisms underlying operations and performance of such novel type of mode-locked lasers with tens of km length scale presents an exciting new area of research in laser science.

The experimental setup based on an all-fibre ring cavity configuration is schematically illustrated in Fig. 1. The cavity consists of 1.5 meter of active erbium-doped fibre with the absorption coefficient of ~ 80 ± 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 mW was launched through a wavelength-division-multiplexed coupler in the opposite direction to the circulation of light generated around 1554 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.

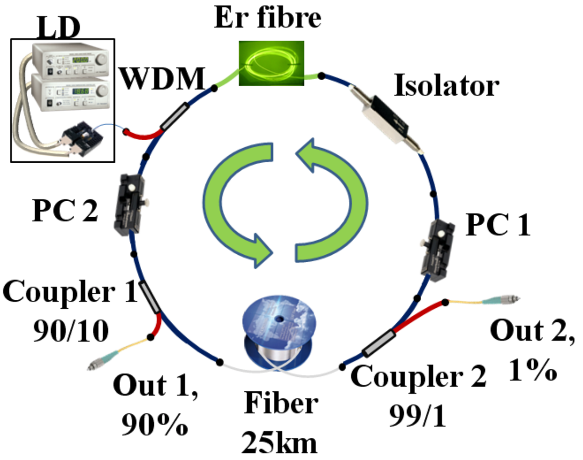

FIG 1. Schematic depiction of the 25-km long ring fibre laser design.

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. Figures 2 and 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 FWHM of 2,5 ns, respectively. The train of pulses has a period of 123.5 μs which corresponds to a 8.097 kHz repetition rate. **Fluctuations of pulse intensity in the monitored pulse train did not exceed 10%.**

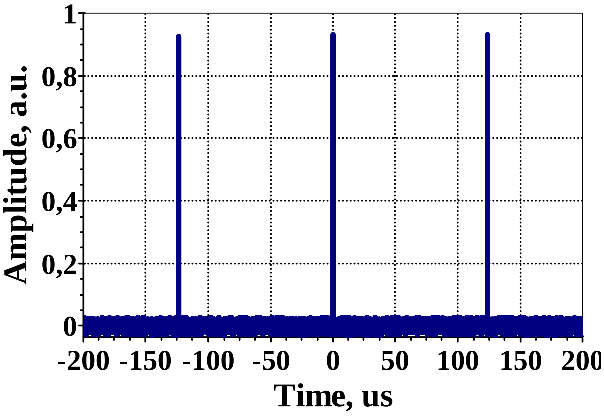

FIG 2. Measured comb of pulses with a mode-locking repetition rate $T_R = nL / c \approx 123.5\ \mu s$.

The central wavelength of lasing is 1554.3 nm with the width of the optical spectrum in the mode locking regime of 0.5 nm (Fig. 4). The temporal duration of bandwidth limited pulse corresponding to the spectrum of 0.5 nm shown in Fig. 4 is around 5 ps assuming sech^2 pulse shape, therefore, we believe laser operates with highly stretched pulses with large chirp.

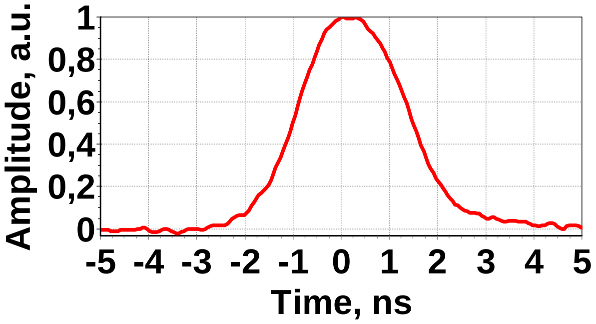

FIG 3. Temporal profile of the generated pulse measured at the output 1.

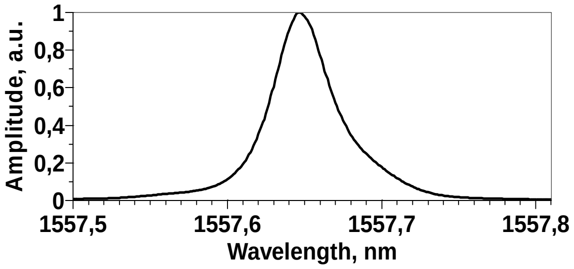

FIG 4. Spectrum of the generated pulse.

For single pulse operation, the average power (output 1) was limited to a maximum of approximately 30 mW corresponding to energy per pulse of 3.7 μJ and peak pulse power of 387 W. The previous maximum value of the pulse energy of a mode-locked Er fibre master oscillator was 0.28 μJ [12] with total laser resonator length shorter by factor of 20 (1.25 km).

3. DISCUSSION

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 right balance between the total normal accumulated dispersion and nonlinear effects.** 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: $C \approx T_p \times \frac{2\pi\,\Delta\lambda\, c}{\lambda_0^2\,(1.665)^2} \approx 985$. 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 [13-21]. Note that no special narrow band filter limiting laser radiation spectrum was used in a stable mode-locked operation, unlike the regimes reported in [16, 19]. 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.

4. CONCLUSIONS

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 [22]. Therefore, we believe that our results might open a new research area of ultra-long mode-locked lasers. 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. In addition, ultra-long mode-locked fibre lasers might find new applications in recently proposed concept of fully classical reliable key distribution systems [23, 24]. 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 that can be stimulated by our results is investigation of dispersion-managed dissipative soliton regimes [25-27] in such ultra-long mode-locked lasers.

Acknowledgments: The authors acknowledge support of the EPSRC, The Royal Society, and the Russian Ministry of Science and Education.

---

[1] 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).

[2] V. Z. Kolev, M. J. Lederer, and B. Luther-Davies, A. V. Rode, Opt. Lett. **28**, 1275 (2003).

[3] J. U. Kang, R. Posey, R. D. Esman, Opt. Lett. **23**, 1375 (1998).

[4] K. H. Fong, S. Y. Set, and K. Kikuchi, in *Proceedings of IEEE/OSA Optical Fiber Conference (OFC) 2007,* Anaheim, 2007, OTuF2.

[5] S. Kobtsev, S. Kukarin, and Y. Fedotov. Opt. Express **16**, 21936 (2008).

[6] 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.

[7] L. Chen, M. Zhang, C. Zhou, Y. Cai, L. Ren, and Z.Zhang. Electronics Letters **45**, 731 (2009)

[8] M. Zhang , L. Chen, C. Zhou, Y. Cai, L. Ren, and Z. Zhang. Laser Physics Letters **6**, 657 (2009).

[9] X. Tian, M. Tang, P. P. Shum, Y. Gong, C. Lin, S. Fu, and T. Zhang, Opt. Lett. **34**, 1432 (2009).

[10] 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)

[11] V. Denisov, B. Nyushkov, and V. Pivtsov. Quantum Electronics **40**, 25 (2010).

[12] X. Tian, M. Tang, X. Cheng, P. Shum, Y. Gong, and C. Lin. Opt. Express **17**, 7222 (2009).

[13] A. Chong, J. Buckley, W. Renninger, and F. Wise. Optics Express, **14**, 10095 (2006).

[14] L. M. Zhao, D. Y. Tang, and J. Wu, Opt. Lett., **31**, 1788-1790 (2006)

[15] V. L. Kalashnikov, E. Podivilov, A. Chernykh, and A. Apolonski. Appl. Phys. **B83**, 503 (2006).

[16] W. Renninger, A. Chong, and F. W. Wise. Physical Review **A77**, 023814 (2008).

[17] N. Akhmediev, J. M. Soto-Crespo, and P.Grelu. Phys. Lett. **A372**, 3124 (2008).

[18] A. Chong, W. H. Renninger, and F. W. Wise. J. Opt. Soc. Am. **B25**, 140 (2008); G. Bale, J. N Kutz, A. Chong, W. H. Renninger, and F. W. Wise, J. Opt. Soc. Am. **B 25**, 1763 (2008).

[19] F. W. Wise, A. Chong, and W. H. Renninger. Laser and Photon. Rev. **2**, 58 (2008).

[20] X. Wu, D. Tang, H. Zhang, and L. Zhao. Opt. Express **17**, 5580 (2009).

[21] J. M. Soto-Crespo, N. N. Akhmediev, V. V. Afanasjev and S. Wabnitz, Phys. Rev. E **55**, 4783 (1997).

[22] S. Kobtsev, S. Kukarin, S. Smirnov, S. Turitsyn, and A. Latkin. Opt. Express **17**, 20707 (2009).

[23] J. Scheuer, A. Yariv. Physical Review Letters **97**, 140502 (2006).

[24] A. Zadok, J. Scheuer, J. Sendowski, A. Yariv. Opt. Express **16**, 16680 (2008)

[25] B. G. Bale, S. Boscolo, and S. K. Turitsyn, Opt. Lett., **34**, 1193 (2009).

[26] N. J. Kutz, SIAM Review, **48,** 629 (2006)

[27] *Dissipative Solitons: From optics to biology and medicine* , edited by N. Akhmediev and A. Ankiewicz, (Lecture Notes in Physics, V. 751, Springer, Berlin-Heidelberg, 2008).