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Cavity topologies of mode-locked fibre lasers: possibilities and prospects

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Abstract. **We report, for the first time, the results of a comparative analysis of cavity topologies in mode-locked fibre lasers. It is shown that the use of various topologies and advantages of fibre technologies allows one to realise the specified combinations of dispersion, nonlinear, polarisation and other properties of fibre laser cavities, difficult to implement or not implementable using the methods of traditional discrete laser optics. The results of the work make it possible to consider the topological engineering of mode-locked fibre lasers as a new, rapidly growing field of research and development.**

Keywords: *mode locking, fibre lasers, laser cavity technology.*

1. Introduction

Fibre laser technology provides new unique possibilities for configuring laser cavities. These possibilities are most expressed in short-pulse fibre lasers, the cavities of which are configured to provide the specific nonlinear, dispersion, polarisation and other properties necessary for reliable locking of the radiation modes [1 – 5]. The rapidly developing fibre technologies for designing cavities of fibre lasers [6 – 10] are somewhat similar to modern meccano sets for assembling and modelling various objects. Various fibre elements with standard connectors or without connectors, but capable of being connected using special equipment, are assembled in a certain sequence, often forming configurations that are difficult to implement basing on discrete optics in traditional solid-state and other lasers.

The wide possibilities of using the fibre laser meccano are largely determined by the relatively high gain of the fibre active medium, which compensates for radiation losses in both the cavity elements and the splice points of optical fibres. Whereas in conventional discrete cavities of short-pulse solid-state lasers, radiation losses of 20 % – 30 % or higher may be unacceptable either because the losses exceed the gain, or because the intracavity power is insufficient for passive mode locking, for many fibre cavities this level of losses is not critical for pulsed oscillation. The lower sensitivity of fibre laser cavities to radiation losses allows a wider implementation of new unique laser resonator configurations and gives rise to a new line of research and development of fibre lasers related to the topology of their cavities.

As shown by numerous studies in recent years, the topology of a cavity of a mode-locked fibre laser (MLFL) can significantly affect the lasing properties, and in many cases determine them. Thus, the topology of a MLFL cavity is an important factor determining the lasing properties. As already mentioned above, the sequence of optical elements in a MLFL cavity has a noticeable effect on the parameters of the generated pulses [11]. However, many newer MLFL cavities are significantly more complex than traditional linear or ring cavity configurations, and in these more complex cavities, the parameters of the generated pulses depend not only on the sequence of optical elements, but also on the geometrical and topological structure of the cavity. This structure includes nontrivial spatial distribution of the nonlinear, dispersion, polarisation and other characteristics of the cavity. The analysis of the key modern geometrical and topological structures of the MLFL cavities has not yet been carried out, and the present work fills this gap.

2. Modifications of the all-fibre ring topology of the cavity

The ring cavity is most often used as the base for the designs of various MLFLs. The main advantage of the ring cavity is the absence of the need to use cavity mirrors, while the radiation is coupled out from the cavity through a fibre coupler. Fibre lasers with linear cavities are also capable of providing high quality mode locking [12 – 14], but linear schemes of such lasers require the use of end wideband mirrors. The latter are still relatively complex and expensive in fibre implementation using both Faraday mirrors [15] or chirped Bragg reflectors [16] and loop reflectors based on fibre circulators [17] or nonlinear optical loop mirrors (NOLMs) [18]. In this connection, ring fibre cavities are most widely used, and most of the cavity topologies of modern MLFLs are the modifications of the traditional classical ring scheme. Passive mode locking in fibre lasers is implemented using either real saturable absorbers [19 – 21] or the so-called artificial saturable absorbers, i.e., intensity discriminators based on optical nonlinearity in fibres [22 – 24].

Typical ring erbium-doped fibre lasers ($\lambda \approx 1.5$ μm) based on conventional single-mode fibres, depending on the passive mode locking method, the cavity dispersion map, and the width of the operational spectral band of intracavity elements, generate ultrashort pulses with durations from a few picoseconds [25] to less than 100 fs [26]. Under condi-

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tions of predominantly anomalous intracavity dispersion in typical erbium lasers, the energy of the generated pulses is usually less than 1 nJ. In all-fibre ring ytterbium lasers ($\lambda \approx 1.1$ μm) mode-locked under conditions of fully normal intracavity dispersion and gain filtering, so-called dissipative solitons are generated [2], which under certain conditions can be compressed with an external compressor to the extreme durations smaller than 100 fs [27, 28].

The fact that a mode-locked pulse can circulate in the cavity under the conditions of completely normal intracavity dispersion, without breaking even when acquiring a large nonlinear phase shift ($\Phi_{\rm nl} \gg \pi$) [29], opened the possibilities for pulse energy scaling. Some work in this direction was based on increasing the intracavity power due to the use of active double-clad fibres and high-power pumping [28]. However, a more interesting approach, which determined a new promising direction for the improvement and development of MLFL topologies, was the pulse energy scaling by increasing the cavity length. This concept is based on the fact that increasing the length of the MLFL cavity leads to a decrease in the fundamental pulse repetition rate and to a proportional increase in pulse energy, the average radiation power (or pump power) being unchanged. Impressive results of pulse energy scaling to the level of microjoules directly in the master fibre oscillator using an ultra-long (2.6 km) cavity were first obtained in an ytterbium fibre laser [30] with a hybrid fibre discrete cavity design. Soon, a similar approach was successfully applied in an all-fibre erbium laser with a kilometre-long cavity [31]. After the first demonstrations of an ultra-long MLFL, many theoretical and experimental studies of lasers of this type followed, reaching a record-high pulse energy of 12 μJ [32] directly at the MLFL output.

The final idea of this approach is to increase the length of a fibre laser cavity with normal dispersion to obtain high-energy strongly chirped pulses, and then compress them and obtain high pulse energy combined with relatively short pulse duration. Practically, the production of well-compressible pulses in an ultra-long fibre cavity is not always ensured, since among the possible oscillation regimes [33], the regime of generating weakly compressible double-scale pulses [34] becomes more stable with an increase in the cavity length. The possibility of highly efficient (by nearly 100 times) compression of single-scale coherent pulses [35] has been demonstrated so far in a cavity only 1 km long, whereas mode locking is implemented in cavities up to 25 km long [36]. To obtain well-compressible high-energy pulses in ultra-long cavities, the development of more advanced cavity topologies is particularly required.

Another important problem of the approach based on a significant increase in the length of the MLFL cavity is the deterioration of the stability of the lasing parameters due to its increased sensitivity to environmental factors (vibrations, temperature and pressure variations). Firstly, this can cause significant polarisation instability of radiation. To solve this problem, it is possible to use special polarisation-maintaining fibres. However, this is associated with a number of other problems: firstly, such fibres are much more expensive than ordinary single-mode fibres, secondly, they have much greater optical losses and, thirdly, the choice of commercially available polarisation-maintaining fibres is relatively narrow. Respectively, the choice of the dispersion characteristics of these fibres is limited too, although they are especially important when fabricating erbium MLFLs. Nevertheless, an original modification of the ring topology of the cavity for an ultra-long MLFL based on polarisation-maintaining fibres was recently demonstrated [37]. The proposed Θ-shaped configuration of a fibre laser, shown schematically in Fig. 1a, makes it possible to use economically the polarisation-maintaining fibre due to the double passage of radiation through the upper loop of the cavity in one roundtrip cycle.

Another topological solution to the problem of the polarisation instability of radiation in ultra-long MLFLs is to use a combined linear-ring cavity configuration in which a super-long linear arm, terminated by a Faraday mirror, is coupled to a relatively short ring cavity (Fig. 1b). The Faraday mirror fully compensates for linear birefringence (and, hence, its fluctuations) in the linear arm. This approach was successfully tested in [31, 38]. An additional advantage of such an ultra-long MLFL cavity topology is the double passage of radiation through the linear arm of the cavity, which is important when special fibres are used in the linear arm, for example, fibres with specified dispersion characteristics.

The linear-ring cavity topology was further developed in Ref. [39], in which the ultra-long MLFL with a γ-shaped cavity configuration was first implemented (Fig. 1c). In this laser, a combination of various types of fibre refractive index gratings was also used for the first time. An additional linear arm with a filter based on a fibre Bragg grating made it possible to optimise the mode-locking regime in the γ-laser, achieve stable generation of high-energy pulses having the typical properties of dissipative solitons, and minimise the contribution of spontaneous emission to the output radiation.

The recently implemented original two-ring cavity topology (Fig. 1d) for an ultra-long high-energy MLFL with high pulse energy [40] deserves special mention. In this laser, a hybrid oscillation regime is realised, in which the mode locking occurs due to an additional (passive) optical feedback ring, the delay in which coincides with the repetition period of pulses, initially arising due to Q-switching in the main (amplifying) ring of the cavity. The pulses with energy up to 4.5 μJ were obtained.

In parallel with the development of modified topologies, research was carried out related to a finer optimisation of the proper ring topology of the MLFL cavities, intended for the generation of high-energy pulses. An actual problem in the implementation of passive mode locking with high intracavity power may be the so-called overdriving of the used mode locking mechanism. This means that when the radiation intensity exceeds a certain level, the transmission function of the artificial saturable absorber is no more monotonically dependent on the instantaneous value of the radiation intensity. This problem can largely manifest itself in mode-locked lasers based on the effect of nonlinear polarisation rotation (NPR) [22] and can be one of the reasons for the formation of so-called double-scale pulses [33, 34]. A possible way to optimise the ring topology of a MLFL cavity in order to solve this problem, as well as the problem of the parasitic stimulated Raman scattering, is demonstrated in Refs [41, 42]. The essence of the approach consists in composing a cavity from a short piece of single-mode fibre (for optimal NPR) and a long piece of polarisation-maintaining fibre (for scaling the pulse energy). In addition, the possibility of mode locking based on the NPR effect in a ring cavity, completely composed of polarisation-maintaining fibres, was recently demonstrated [43]. In such a cavity, the slow axes of consecutive segments of spliced birefringent fibres

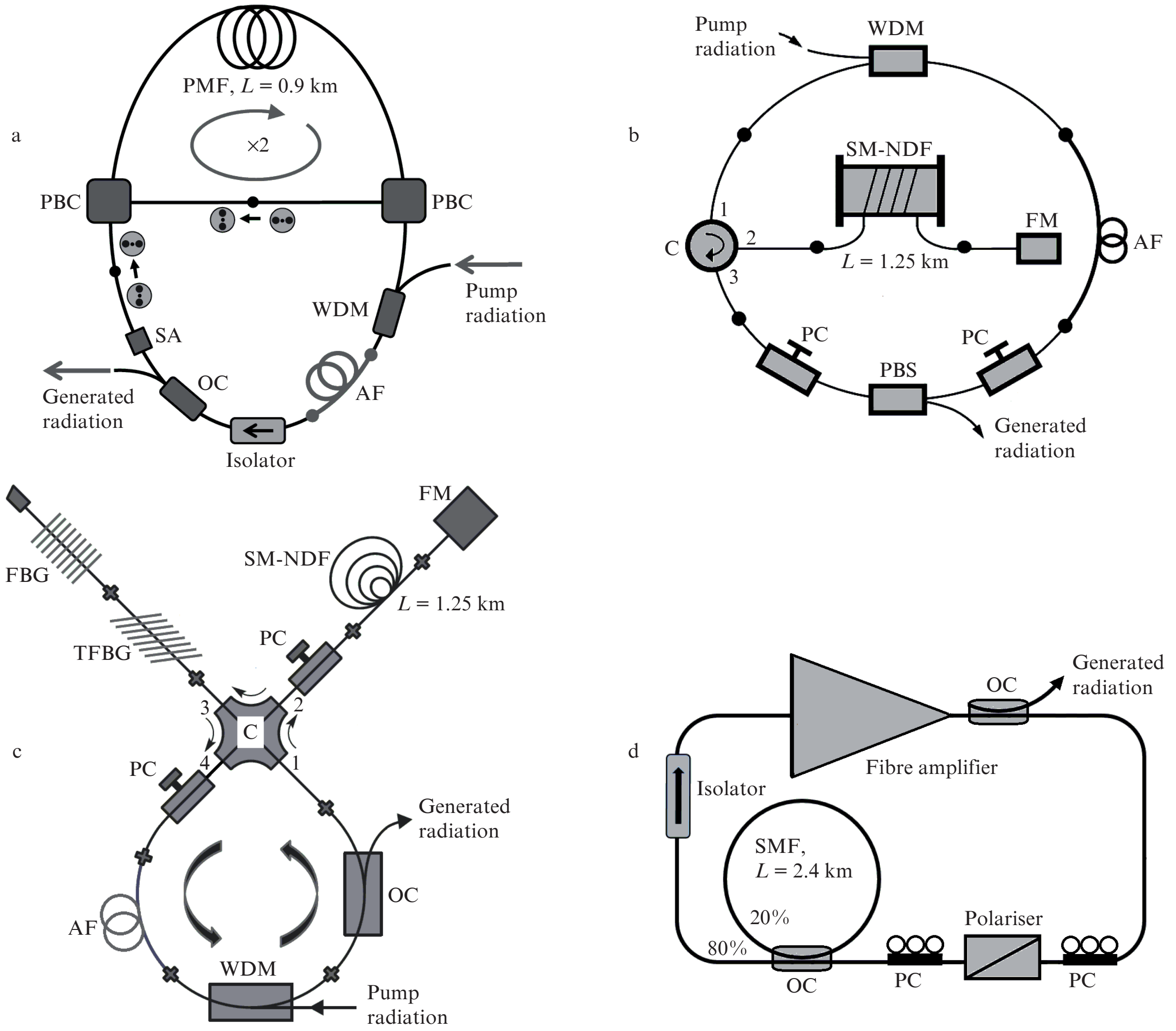

Figure 1. Schematics of ultra-long MLFLs with different cavity topologies: (a) Θ-cavity [37]; (b) linear-ring cavity [31, 38]; (c) γ-cavity [39]; (d) coupled two-ring cavity [40]. Notations are as follows: (PMF) polarisation-maintaining fibre, (PBC) polarisation beam combiner, (SA) saturable absorber, (OC) optical coupler, (AF) active fibre, (WDM) wavelength division multiplexer, (FBG) fibre Bragg grating, (TFBG) tilted fibre Bragg grating, (C) circulator, (PC) polarisation controller, (SM-NDF) single-mode normal dispersion fibre, (FM) Faraday mirror, (PBS) polarisation beam splitter, (SMF) single-mode fibre.

are oriented at certain angles to each other. This allows using NPR and compensating for the negative effect of linear birefringence on the ultrashort pulse. A further development of this approach is the topology that combines the noncollinear orientation of the slow axes of consecutive segments of birefringent fibres with the use of a Faraday mirror [44, 45].

3. Cavity topologies with the possibility to control and stabilise the frequency–time characteristics of the MLFL

The ring topology modifications of the cavities considered above are mainly aimed at the generation of pulses with relatively high energy and low repetition rate. Lasers with such parameters can be used for precision processing of artificial materials and biological tissues, for lidar measurements and long-distance optical communication through the Earth's atmosphere. However, to solve a number of other problems, for example, those associated with modern methods of time and frequency metrology [46, 47], highly stable sources of ultrashort light pulses are needed, the basic requirements for which are not associated exclusively with high pulse energy. For these tasks, femtosecond fibre lasers with the possibility of fine tuning and dynamic adjustment of the frequency–time characteristics of the radiation (for example, pulse repetition rate, centre wavelength of oscillation) are necessary. Thus, to produce highly stable optical frequency combs [5, 48] or optical frequency synthesisers [49], which are the basis of an optical clock, femtosecond sources with a high pulse repetition rate (no less than 100 MHz) and pulses as short as possible ($<$100 fs) are preferable. The topology of the cavities of such lasers should provide the possibility of efficient automatic control of the optical length of the cavity to stabilise the intermode frequency spacing (pulse repetition rate), as well as the ability to control the intracavity dispersion and, thus, the offset frequency of the generated optical frequency comb.

For a long time, when producing highly stable erbium MLFLs for metrological purposes, both simple ring cavities of adjustable length [50] and σ-cavities like those shown in Fig. 2a, particularly preferable in commercial systems [51], were used. The linear-ring fibre-discrete topology of such a cavity is based on the use of a polarisation beam splitter that couples the fibre ring part of the cavity to a short linear arm consisting of discrete optics. The polarisation splitter also plays the role of a polarisation discriminator, which is necessary to maintain the mode-locking regime due to the NPR effect. This topology of the cavity retains some advantages of the ring topology, provides a high fundamental pulse repetition rate (up to 250 MHz in commercial models) due to the small optical length. It also provides a large dynamic range and high speed of its adjustment due to the combined use of a piezotranslator and an electro-optical modulator in the linear part of the cavity. The latter also allows the integration of adjustable dispersion wedges. The disadvantages of this topology include the need for using a number of precisely aligned discrete optical elements, which complicates the design and places high demands on its mechanical stability. The similars linear-ring topology of a cavity with adjustable length can also be implemented using a fibre circulator [52].

Recently, an alternative topology of a MLFL cavity has been proposed, which, like the σ-cavity, may have a small optical length and allows it to be tuned dynamically. In this case, the cavity comprises only one discrete optical element, which requires precise alignment. The proposed drop-shaped topology of the cavity [53], schematically presented in Fig. 2b, is based on the integral dual-fibre collimator (DFC) of radiation. Its design allows extracting radiation from both fibre ports in the form of beams intersecting near the focal point of the collimating lens. Accordingly, with the help of a mirror installed near this point, the radiation from one DFC fibre port can be redirected to another. Thus, using DFC, the all-fibre ring topology of the cavity can be transformed into the drop-like topology, which allows dynamic tuning of the opti-

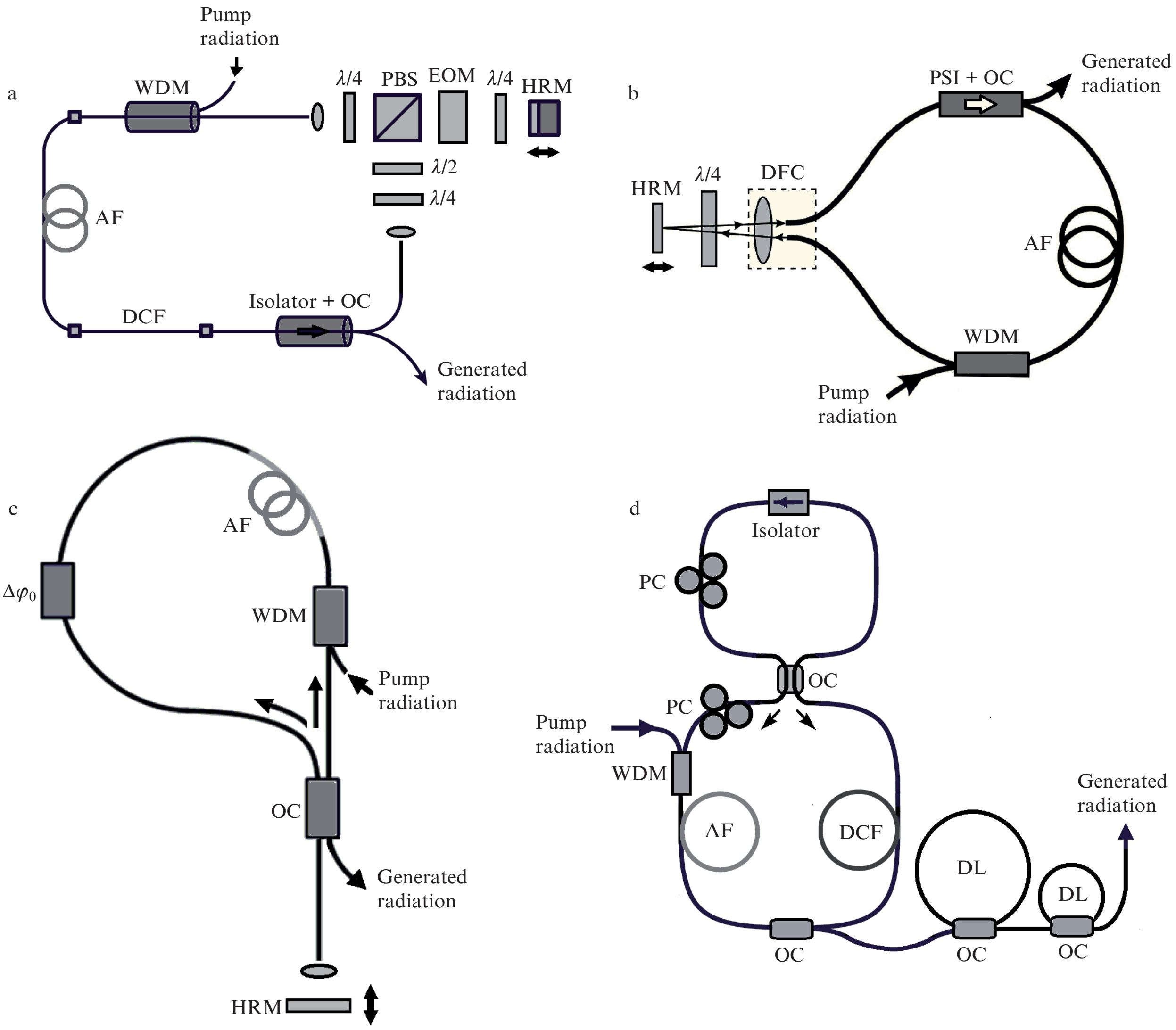

Figure 2. MLFL schemes with various cavity topologies that provide the possibility of controlling and stabilising the frequency–time characteristics of the radiation: (a) σ-cavity [51]; (b) drop-shaped cavity [53]; (c) ‘figure-9’ cavity [54, 56]; (d) ‘figure-8’ cavity with additional passive rings to increase the pulse repetition rate [57]. Notations are as follows: (DCF) dispersion compensating fibre, (PBS) polarisation beam splitter, (EOM) electro-optical modulator, ($\lambda/2$) and ($\lambda/4$) phase plates, (HRM) highly reflecting mirror, (DFC) dual-fibre collimator, (PSI) polarisation-sensitive isolator, ($\Delta\varphi_0$) initial phase shift, (DL) delay line (other notations are the same as in Fig. 1).

cal length of the cavity by a small displacement of the mirror near the DFC focal point. In addition, the proposed configuration allows the installation of a compact electro-optical modulator between the DFC and the mirror to increase the tuning speed.

Recently, in metrological femtosecond fibre-laser systems they began to use MLFLs, in which the topology of the cavities is called 'figure-9' [54–56]. This type of cavity is an improved modification of the previously widespread 'figure-8' topology [57–59]. The mode locking in both types of cavities is carried out by an artificial saturable absorber, which is formed by a nonlinear amplifying loop mirror (NALM). An important advantage of using NALMs over mode locking due to the NPR is the possibility of implementing MLFL completely based on polarisation-maintaining fibres without the use of adjustable phase plates or polarisation controllers [54, 56]. Thus, it is possible to realise a femtosecond oscillator that is resistant to external influences and does not require periodic adjustment to initiate mode locking. In comparison with 'figure-8' cavities, the lasers with a 'figure-9' type cavity have a smaller optical length, which allows a higher fundamental repetition rate of femtosecond pulses, up to 250 MHz [56]. The linear part of the 'figure-9' cavities in metrological MLFLs is implemented using discrete optical elements to minimise the optical length and to provide the possibility of its tuning [54, 56]. Despite the presence of discrete elements, their adjustment does not have such a critical effect on the mode-locking operation, as in the case of classical σ-cavities with mode locking due to the effect of NPR. Figure 2c schematically shows the MLFL with the 'figure-9' topology [54], and Fig. 2d shows the one with the extended 'figure-8' topology, supplemented by passive rings to increase the pulse repetition rate [57]. It is also necessary to mention the recently demonstrated improvement in the configuration of the NALM for the MLFLs with the 'figure-8' topology based on polarisation-maintaining fibres [60, 61]. In the new configuration of the NALM, two separately controlled fibre-optical gain sections are used. This extends the possibilities of regulating and optimising the parameters of pulsed generation, in particular, allows the peak power of pulses to vary over a wide range.

4. Conclusions

Modern topological structures of MLFL cavities are very diverse, allowing the use of unique combinations of properties of different types of fibre cavities. The rapid development of fibre technologies makes it possible to design fundamentally new fibre cavity configurations that are capable of achieving record-breaking parameters and higher quality of oscillation in the mode-locking regime, as well as provide enhanced control and management capabilities for the MLFL characteristics. The results of this work allow us to consider topological engineering of fibre lasers with mode-locked radiation as a new, rapidly grwoing, promising area of research and development.

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References

1. Kutz J.N. *SIAM Rev*., **48**, 629 (2006).
2. Grelu P., Akhmediev N. *Nat. Photon*., **6**, 84 (2012).
3. Fermann M.E., Hartl I. *Nat. Photon*., **7**, 868 (2013).
4. Brida D., Krauss G., Sell A., Leitenstorfer A. *Laser Photon. Rev*., **8**, 409 (2014).
5. Kim J., Song Y. *Adv. Opt. Photon*., **8**, 465 (2016).
6. Adel P. *Pulsed Fiber Lasers* (Gottingen: Cuvillier Verlag, 2004).
7. Fermann M.E., Hartl I. *IEEE J. Sel. Top. Quantum Electron*., **15**, 191 (2009).
8. Paul M.C. (Ed.) *Fiber Lasers: Advances in Research and Applications* (New York: Nova Science Publ., 2017).
9. Zhou P., Wang X., Xiao H., Ma Y., Chen J. *Laser Phys*., **22**, 823 (2012).
10. Dong L., Samson B. *Fiber Lasers: Basics, Technology, and Applications* (Boca Raton: CRC Press, 2016). ISBN-10: 1498725546/ISBN-13:978-1498725545.
11. Shtyrina O.V., Yarutkina I.A., Skidin A., Fedoruk M.P., Turitsyn S.K. *IEEE Photon. J*., **7**, 1501207 (2015).
12. Liu J., Wang Q., Wang P. *Opt. Express*, **20**, 22442 (2012).
13. Litago I.A., Leandro D., Quintela M.A., Pérez-Herrera R.A., López-Amo M., López-Higuera J.M. *J. Lightwave Technol*., **35**, 5003 (2017).
14. Lau K.Y., Ng E.K., Abu Bakar M.H., Abas A.F., Alresheedi M.T., Yusoff Z., Mahdi M.A. *Opt. Laser Technol*., **102**, 240 (2018).
15. Hekmat M.J., Gholami A., Omoomi M., Abdollahi M., Bagheri A., Normohammadi H., Kanani M., Ebrahimi A. *Laser Phys. Lett*., **15**, 025101 (2018).
16. Han X.X. *Laser Phys*., **25**, 025104 (2015).
17. Kobtsev S., Kukarin S., Smirnov S., Fedotov Y. *Proc. SPIE*, **7580**, 758023 (2010).
18. Wang P., Tang Y., Peng H., Shi G., He T., Li H., Liu Y. *J. Mod. Opt*., **64**, 122 (2017).
19. Chernysheva M., Rozhin A., Fedotov Y., Mou C., Arif R., Kobtsev S.M., Dianov E.M., Turitsyn S.K. *Nanophotonics*, **6**, 1 (2017).
20. Mao D., Wang Y., Ma C., Han L., Jiang B., Gan X., Hua S., Zhang W., Mei T., Zhao J. *Sci. Rep*., **5**, 7965 (2015).
21. Lee J., Koo J., Jhon Y.M., Lee J.H. *Opt. Express*, **22**, 6165 (2014).
22. Matsas V.J., Newson T.P., Richardson D.J., Payne D.N. *Electron. Lett*., **28**, 1391 (1992).
23. Doran N.J., Wood D. *Opt. Lett*., **13**, 56 (1988).
24. Fermann M.E., Haberl F., Hofer M., Hochreiter H. *Opt. Lett*., **15**, 752 (1990).
25. Kobtsev S., Ivanenko A., Gladush Y.G., Nyushkov B., Kokhanovskiy A., Anisimov A.S., Nasibulin A.G. *Opt. Express*, **24**, 28768 (2016).
26. Zhang Z., Mou C., Yan Z., Zhou K., Zhang L., Turitsyn S. *Opt. Express*, **21**, 28297 (2013).
27. Mortag D., Wandt D., Morgner U., Kracht D., Neumann J. *Opt. Express*, **19**, 546 (2011).
28. Kieu K., Renninger W.H., Chong A., Wise F.W. *Opt. Lett*., **34**, 593 (2009).
29. Wise F.W., Chong A., Renninger W.H. *Laser Photon.Rev*., **2**, 58 (2008).
30. Kobtsev S., Kukarin S., Fedotov Y. *Opt. Express*, **16**, 21936 (2008).
31. Nyushkov B.N., Denisov V.I., Kobtsev S.M., Pivtsov V.S., Kolyada N.A., Ivanenko A.V., Turitsyn S.K. *Laser Phys. Lett*., **7**, 661 (2010).
32. Ivanenko A., Kobtsev S., Smirnov S., Kemmer A. *Opt. Express*, **24**, 6650 (2016).
33. Smirnov S., Kobtsev S., Kukarin S., Ivanenko A. *Opt. Express*, **20**, 27447 (2012).
34. Kobtsev S., Kukarin S., Smirnov S., Turitsyn S., Latkin A. *Opt. Express*, **17**, 20707 (2009).
35. Woodward R.I., Kelleher E.J.R., Runcorn T.H., Loranger S., Popa D., Wittwer V.J., Ferrari A.C., Popov S.V., Kashyap R., Taylor J.R. *Opt. Lett*., **40**, 387 (2015).
36. Ivanenko A., Turitsyn S., Kobsev S., Dubov M. *36th European Conf. Exhibition on Optical Communication (ECOC 2010)* (Torino, Italy, 2010) Tu.5.D.1.
37. Senoo Y., Nishizawa N., Sakakibara Y., Sumimura K., Itoga E., Kataura H., Itoh K. *Opt. Express*, **18**, 20673 (2010).
38. Denisov V.I., Nyushkov B.N., Pivtsov V.S. *Quantum Electron*., **40**, 25 (2010) [*Kvantovaya Elektron*., **40**, 25 (2010)].

39. Nyushkov B.N., Ivanenko A.V., Kobtsev S.M., Turitsyn S.K., Mou C., Zhang L., Denisov V.I., Pivtsov V.S. *Laser Phys. Lett.*, **9**, 59 (2012).
40. Braham F.B., Semaan G., Niang A., Komarov A., Bahloul F., Salhi M., Komarov K., Sanchez F. *Laser Phys. Lett.*, **15**, 095401 (2018).
41. Bednyakova A.E., Babin S.A., Kharenko D.S., Podivilov E.V., Fedoruk M.P., Kalashnikov V.L., Apolonski A. *Opt. Express*, **21**, 20556 (2013).
42. Kharenko D.S., Gonta V.A., Babin S.A. *Laser Phys. Lett.*, **13**, 025107 (2016).
43. Szczepanek J., Kardaś T.M., Radzewicz C., Stepanenko Y. *Opt. Lett.*, **42**, 575 (2017).
44. Szczepanek J., Kardaś T.M., Radzewicz C., Stepanenko Y. *Opt. Express*, **26**, 13590 (2018).
45. Zhou J., Pan W., Gu X., Zhang L., Feng Y. *Opt. Express*, **26**, 4166 (2018).
46. Ye J., Cundiff S.T. (Eds). *Femtosecond Optical Frequency Comb Technology: Principle, Operation and Application* (New York: Springer, 2005).
47. Beverini N., Carelli G., De Michele A., Maccioni E., Nyushkov B., Sorrentino F., Moretti A. *Opt. Lett.*, **30**, 32 (2005).
48. Droste S., Ycas G., Washburn B.R., Coddington I., Newbury N.R. *Nanophotonics*, **5**, 196 (2016).
49. Pivtsov V.S., Nyushkov B.N., Korel I.I., Kolyada N.A., Farnosov S.A., Denisov V.I. *Quantum Electron.*, **44**, 507 (2014) [*Kvantovaya Elektron.*, **44**, 507 (2014)].
50. Gubin M.A., Kireev A.N., Konyashchenko A.V., Kryukov P.G., Shelkovnikov A.S., Tausenev A.V., Tyurikov D.A. *Appl. Phys. B*, **95**, 661 (2009).
51. Nyushkov B.N., Pivtsov V.S., Kolyada N.A., Kaplun A. B., Meshalkin A. B. *Quantum Electron.*, **45**, 486 (2015) [*Kvantovaya Elektron.*, **45**, 486 (2015)].
52. Denisov V.I., Ivanenko A.V., Nyushkov B.N., Pivtsov V.S. *Quantum Electron.*, **38**, 801 (2008) [*Kvantovaya Elektron.*, **38**, 801 (2008)].
53. Nyushkov B.N., Kobtsev S.M., Koliada N.A., Antropov A.A., Pivtsov V.S., Yakovlev A.V. *Laser Phys. Lett.*, **14**, 115101 (2017).
54. Kuse N., Jiang J., Lee C.-C., Schibli T.R., Fermann M.E. *Opt. Express*, **24**, 3095 (2016).
55. Krzempek K., Sotor J., Abramski K. *Opt. Lett.*, **41**, 4995 (2016).
56. Hänsel W., Hoogland H., Giunta M., Schmid S., Steinmetz T., Doubek R., Mayer P., Dobner S., Cleff C., Fischer M., Holzwarth R. *Appl. Phys. B*, **123**, 41 (2017).
57. Zhao Y., Min S., Wang H., Fleming S. *Opt. Express*, **14**, 10475 (2006).
58. Wang S.K., Ning Q.Y., Luo A.P., Lin Z.B., Luo Z.C., Xu W.C. *Opt. Express*, **21**, 2402 (2013).
59. Pottiez O., Grajales-Coutiño R., Ibarra-Escamilla B., Kuzin E.A., Hernández-García J.C. *Appl. Opt.*, **50**, E24 (2011).
60. Smirnov S., Kobtsev S., Ivanenko A., Kokhanovskiy A., Kemmer A., Gervaziev M. *Opt. Lett.*, **42**, 1732 (2017).
61. Kokhanovskiy A., Kobtsev S., Ivanenko A., Smirnov S. *Laser Phys. Lett.*, **15**, 125101 (2018).