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Towards the "dream pulsed laser"

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ABSTRACT

It is an obvious trend that more and more technology devices are approaching the stage of computer-controlled black box, and lasers cannot escape this either. Generally, users do not want to understand the operation of a black box. They just want to set the output radiation parameters through their computer and have a magic black box deliver the desired radiation. In addition, they expect this technology to be reliable and inexpensive. The most fitting laser platforms for this type of technology are semiconductor and fibre-optical, which do not require optical alignment of laser cavities and have been performing very well in a numerous applications. Here, we analyse the fibre laser platform from the viewpoint of using it as a base for implementation of a "dream pulsed laser" and discuss limitations and prospects of such implementation.

1. Introduction

It is impossible to make a single universal laser for all needs. Many problems that have been studied for years (or even decades) require very specific optical radiation with well-defined parameters. For example, welding of car bodies calls for a particular laser, whereas fibre Bragg gratings are fabricated with a widely different type of laser, etc. In this discussion, we try to understand how far it may be possible to extend the capabilities of the fibre-optical platform to implement a laser combining alignment- and maintenance-free operation with convenient electronic control of the output parameters.

A small "black box" connected to a portable computer or a mobile device, from which a simple interface allows setting the average output power (or the peak pulse power), wavelength and/or pulse duration looks already like the "dream pulsed laser" (Fig. 1) whose parameters may be adaptively set to the requirements of your new projects. It could also have a touch screen on the black box itself or on a separate electronic control unit linked to the laser head either with a cable or wirelessly.

For continuous-wave output, such dream lasers already exist as solid-state pump lasers [1], fibre [2], or think-disk [3] lasers, all widely employed in industry. In contrast, pulsed laser systems, and short-pulsed ones (fs, ps) in particular, are considerably more complicated (due to more involved method of short pulse generation, modification of the laser cavity properties caused by variation of pump radiation power, etc. [4]). Therefore, the "dream pulsed laser" is still at the development stage, and this stage has now been dragging on for many years. It will not be an overstatement to say that all modern laser design and manufacture has a firm trend to black-box implementation—there are fewer and fewer customers willing to put up with manual knob adjustment and optical element cleaning. Researchers come to expect from light sources—lasers—the same convenience as offered by other energy sources, such as power supplies or electric signal generators. They demand compact dimensions, high efficiency, and trouble-free operation. It was the modern pumping lasers [5], usually solid-state-based and very close to the black-box or "dream laser" concept, that have set a new point of reference for light sources. One of the fundamental inconveniences of these light sources comes from their quite constrained live parameter adjustability. In essence, these pump lasers only allow adjustment of their output power, the other parameters, such as wavelength, remaining fixed. Cavity configurations of these lasers are often quite complicated [6], maybe as complex as those of the lasers, which they are supposed to pump.

Quite naturally, an effort was started to develop such a black-box or a "dream laser", in which there would be at least two adjustable radiation parameters, output power and wavelength. For the moment, this may be sufficient for continuous-wave sources. In comparison, a "dream pulsed laser" would need at least 4 or 5 adjustable parameters: average output power, wavelength and duration of output pulses, repetition rate (or energy parameter of pulses), pulse shape, structure, and so on.

2. Basic platform of the "dream pulsed laser"

It is obvious that the market goal for a laser would be a low-cost device with unlimited service life and broad functional capabilities that does not require servicing and special user qualifications. Such laser

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types as gas or dye lasers can hardly fulfil these expectations, these technologies are receding into the past. Solid-state laser technologies are more modern and better correspond to the mentioned requirements. They may be implemented both in classical volumetric solid-state configurations, semiconductor-based lasers, or fibre lasers. The two former laser types may need very little maintenance and user qualification (for instance, a laser pointer or a laser diode). However, lasers with short or ultra-short cavities suffer from narrow functional capabilities (low volume imposes significant limitations on the devices and methods of control over radiation parameters). Larger cavity volume (such as in classical volumetric solid-state lasers) leads to additional requirements to servicing and user qualification. Fibre lasers appear more suitable as the basis of the “dream pulsed laser” since they are capable of meeting most of the requirements to a modern source of short-pulsed radiation. A problem still remains, however, in relation to controllability of their parameters (ideally, with electronic means). Nevertheless, comparatively long cavities of fibre lasers raise hopes that this problem may be solved in the foreseeable future. Let us consider the possible ways of resolving the problem of control over the radiation parameters of short-pulsed fibre lasers.

We should also point out the drawbacks of the fibre technology as the basic laser platform. First of all, the cost of such platform will scarcely be low because the foundational pieces of this technology are difficult (or expensive) to develop in house, whereas their connection and assembly requires specialised expensive equipment. Secondly, although the fibre optical technology removes the need for servicing of lasers (no optical surfaces to clean or align, etc.), it also takes away in most cases the possibility of in-house repairs (since, again, the same type of specialised equipment is required). Therefore, the fibre-optical platform is by no means ideal in all respects, but it suffers from fewer drawbacks than other platforms.

3. Results

The existing methods make use of electronically controllable action upon the laser cavity fibre relying on two general methods: “internal” and “external” (Fig. 2).

Among the methods of “external” action on the fibre are not only mechanical and thermal effects (fibre tension and torsion [7,8], in particular adjustment of the fibre dispersion when the period of a Bragg grating recorded in the core changes, etc. [9]), but also methods of adjustment of two and more pump radiation sources [10–12]. The problems of “external” action on the fibre consist in that adjustment of a single control parameter may lead to a) modification of several output radiation parameters (variation of the pulse peak power may result in changed duration or wavelength, in particular due to generation of the Raman component) and b) shifting of the generation regime, for example, leading to generation of multi-bound waves. Here we are not discussing CW tandem pumping [13] (which enables strong suppression of ASE) for establishment of uniform gain, even though this approach may be profitable for development of the “dream pulsed laser”. We concentrate, instead, on more straightforward approaches allowing relatively simple computerised control of the radiation parameters of the black box.

As it was mentioned earlier, “external” action on fibre is generally non-trivial, that is adjustment of one “external” parameter may produce not only variation of a single target radiation parameter, but also simultaneous variation of multiple parameters or even modification of the generation regime. Naturally, this complicates development of the “dream pulsed laser” technology. This circumstance, in addition to the general lack of development of fibre-optical technologies themselves, for the moment delays attainment of the “dream pulsed laser”.

The general state of matters related to “internal” action is similar to that of the “external” methods, even though there exist isolated examples of pointed “internal” action [14].

We deliberately avoid research that relies on fibre-optical polarisation controllers [15 and many others] since their settings are, as a rule, unique and not repeatable in conventional laboratory conditions. Furthermore, fibre-based polarisation controllers exhibit noticeable drift of their parameters (arising from glass plasticity) and therefore are not very suitable for commercial products. Correspondingly, it is unlikely that the “dream pulsed laser” could rely on fibre-optical polarisation controllers and use approaches involving them.

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Technologies of selective parameter adjustment appear to be a promising field of research and development on the way to the “dream pulsed laser”. As we demonstrated earlier, these technologies fall into two categories, whereas they should provide (ideally) independent control over 4 or 5 radiation parameters. This means that for independent variation of a few pulse’s parameters must be used standby of some technology or standby of both technologies. In general, one type of action (‘internal’ or ‘external’) may be used to control one output parameter. This means that for independent variation of a few pulse’s parameters, some additional action technologies must likely be used. In approaching the “dream pulsed laser”, the convenience of fibre-optical technology turns into an inconvenience (hopefully, temporal) of the

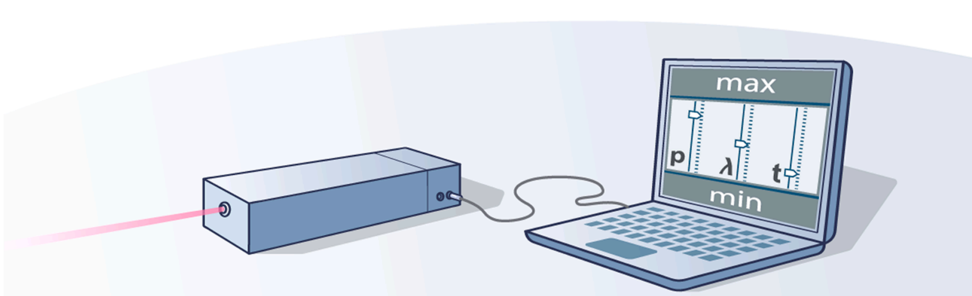

Fig. 1. “Dream pulsed laser” concept.

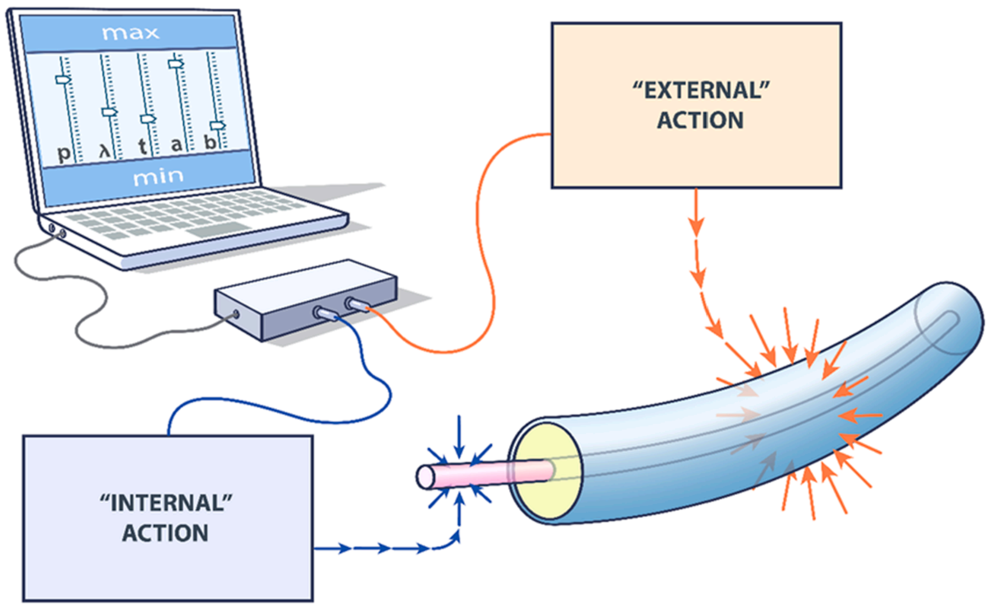

Fig. 2. "External" and "internal" action on a fibre.

means of laser automation. The recent efforts at "teaching" something to such lasers [16–18] have so far been limited to getting, with computer aid, at least something useful, however little, from these lasers, which don't work well with manual control. In our view, this is not the right way towards the "dream pulsed laser".

It must be mentioned that solving the problems of control over the radiation parameters of short-pulsed fibre lasers leads to the opposite situation. On the one hand, it is convenient that the radiation source is implemented as a black box that does not need servicing, does not allow any internal access, and requires no knowledge of its components. On the other hand, however, its radiation parameters should be variable within broad limits, which means that access is required at least to the intra-cavity radiation. Control over certain radiation parameters of fibre lasers (wavelength [19–21], pulse duration [21], and so forth) has already been implemented. The question is how to control all the radiation parameters (or, at least, the majority) in a short-pulsed fibre laser. And this control should be electronic, flexible, and preserving all the advantages of the fibre-optical technology.

Turning to the practical aspects, it should be noted that the 'internal' action is effected primarily through elements integrated into an all-fibre platform. These are elements optically interfaced with fibre and having their volumetric counterparts (birefringent filters, Fabry-Pérot étalons, and so on). They directly affect the laser radiation contained in the fibre core. Direct interaction of such elements with the optical wave propagating along the fibre is an efficient way of control over the laser's output radiation parameters. If the properties of those elements may be modified by electrical signals, it is possible to implement electronic control of the output radiation parameters. This method of control is actively developed in parallel to the development of fibre laser technologies. The 'external' action methods (for example, through the fibre cladding) are currently less advanced. Among those in use to-day, one could mention polarisation controllers (fibre torsion and bending result in variation of radiation polarisation), as well as the methods relying on evanescent field interaction with various elements (these latter require violation of the total internal reflection, — as a rule, only slight, through D-shaped fibre configuration). Mechanical action on the fibre cladding aimed at modification of radiation polarisation inside the core is a simple and popular method. But, first of all, it does not fit all lasers, and, secondly, it cannot be reliably implemented with electronic control. Methods based on evanescent field are more promising, but at the same time more difficult due to requirement of fine processing of fibre. The potential held by the evanescent field methods of control over the radiation parameters is relatively narrow, but progress is likely in this field.

4. Conclusions

In this discussion we use the term "dream pulsed laser" to describe a pulsed source of laser radiation whose parameters are adjustable within broad limits by electronic means for various research and development tasks. Narrow long-term applications do not practically need a universal radiation source, which also happens to provide radiation parameters they require. Therefore, we primarily contemplate the creation of a "dream pulsed laser" designed for scientific applications. Any laboratory would be quite happy to supplement its set of tools with a "dream pulse laser" whose output pulse parameters could be broadly varied. The fibre-optical technology appears the most advantageous in approaching this goal despite fact that automation of such lasers fit for the "dream pulsed laser" concept is currently at the stage of trial and error rather than complete solution. The more interesting are both the problem itself and the methods used to approach it.

It follows from the analysis that the fibre-optical technology has both its strong and weak points. Both arise from the 'closedness' of this technology, which is convenient from the viewpoint of practical operation, but inconvenient from that of external (desirably, electronic) control of radiation parameters. Nevertheless, methods of radiation parameter control in fibre lasers are being advanced through both 'internal' and 'external' types of action upon the radiation of these lasers. It is pertinent to draw the reader's attention both to limited character and narrow possibilities of the 'external' action methods and to their significant potential.

Turning back to the title of this work, it is important to understand that although up to this moment, the fibre-optical technology comes the closest to become the base platform of the "dream pulsed laser", the corresponding available choice of electronic methods of broad-range action upon the radiation is quite limited and certainly does not come close to the 'dream' part in "dream pulsed laser". In relation to short-pulsed technologies, it is important to bear in mind that the technology of these lasers is still at the development stage and the best solutions may still be some way in the making.

CRediT authorship contribution statement

S. Kobtsev: Conceptualization, Investigation, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The data that support the findings of this study are available within the article.

REFERENCES

[1] G. Huber, C. Kränkel, K. Petermann, Solid-state lasers: status and future, J. Opt. Soc. Am. B 27 (2010) B93–B105, https://doi.org/10.1364/JOSAB.27.000B93.

[2] D.J. Richardson, J. Nilsson, W.A. Clarkson, High power fiber lasers: current status and future perspectives, J. Opt. Soc. Am. B 27 (2010) B63–B92. https://doi.org/10.1364/JOSAB.27.000B63; J. Nilsson and D. N. Payne, High-power fiber lasers, Science, 332 (6032) (2011) 921–922. https://doi.org/10.1126/science.1194863.

[3] B. Schmidt, M. Schaefer, Advanced industrial laser systems and applications, Proc. SPIE 10525 (2018) 1052502, https://doi.org/10.1117/12.2299534.

[4] U. Keller, Ultrafast all-solid-state laser technology, Appl. Phys. B 58 (1994) 347–363, https://doi.org/10.1007/BF01081874.

[5] R.L. Byer, Diode laser-pumped solid-state lasers, Science 239 (1988) 742, https://doi.org/10.1126/science.239.4841.742.

[6] D.C. Hanna, W.A. Clarkson, A review of diode-pumped lasers, in: D M. Finlayson, B. Sinclair (Eds.), Advances in Lasers and Applications, Taylor & Francis, New York, 1998. https://eprints.soton.ac.uk/380094/.

[7] H. Kim, E. Lee, B. Kim, Polarization properties of fiber lasers with twist-induced circular birefringence, Appl. Opt. 36 (27) (1997) 6764–6769, https://doi.org/10.1364/AO.36.006764.

[8] A. Paterno, N. Haramoni, J. Silva, H. Kalinowski, Highly reliable strain-tuning of an Erbium-doped fiber laser for the interrogation of multiplexed Bragg grating sensors, Opt. Commun. 273 (2007) 187–192, https://doi.org/10.1016/j.optcom.2006.12.004.

[9] L. Dong, B. Samson, Fiber lasers: basics, technology, and applications, CRC Press, 2016, 340p. https://www.amazon.com/Fiber-Lasers-Basics-Technology-Applications-ebook/dp/B01MTGAJFI.

[10] S. Smirnov, S. Kobtsev, A. Ivanenko, A. Kokhanovskiy, A. Kemmer, M. Gervaziev, Layout of NALM fiber laser with adjustable peak power of generated pulses, Opt. Lett. 42 (2017) 1732–1735, https://doi.org/10.1364/OL.42.001732.

[11] A. Kokhanovskiy, S. Kobtsev, A. Ivanenko, S. Smirnov, Properties of artificial saturable absorbers based on NALM with two pumped active fibres, Las. Phys. Lett. 15 (12) (2018) 125101, https://doi.org/10.1088/1612-202X/aae21c.

[12] A. Kokhanovskiy, E. Kuprikov, S. Kobtsev, Single- and multi-soliton generation in figure-eight mode-locked fibre laser with two active media, Opt. Laser Technol. 131 (2020) 106422, https://doi.org/10.1016/j.optlastec.2020.106422.

[13] A. Malinowski, J. Price, M. Zervas, Overlapped pulsed pumping of tandem pumped fiber amplifiers to increase achievable pulse energy, IEEE J. Quantum Electron. 53 (2) (2017) 1600108, https://doi.org/10.1109/JQE.2017.2657334.

[14] Y. Gladush, A. Mkrtchyan, D. Kopylova, A. Ivanenko, B. Nyushkov, S. Kobtsev, A. Kokhanovskiy, A. Khegai, M. Melkumov, M. Burdanova, M. Staniforth, J. Lloyd-Hughes, A. Nasibulin, Ionic liquid gated carbon nanotube saturable absorber for switchable pulse generation, Nano Lett. 19 (9) (2019) 5836–5843, https://doi.org/10.1021/acs.nanolett.9b01012.

[15] K. Tamura, H. Haus, E. Ippen, Self-starting additive pulse mode-locked erbium fibre ring laser, Electron. Lett. 28 (24) (1992) 2226–2228, https://doi.org/10.1049/el:19921430.

[16] T. Baumeuster, S. Brunton, J. Kutz, Deep learning and model predictive control for self-tuning mode-locked lasers, J. Opt. Soc. Am. B 35 (3) (2018) 617–626, https://doi.org/10.1364/JOSAB.35.000617.

[17] G. Pu, L. Yi, L. Zhang, W. Hu, Intelligent programmable mode-locked fiber laser with a human-like algorithm, Optica 6 (2019) 362–369, https://doi.org/10.1364/OPTICA.6.000362.

[18] G. Genty, L. Salmela, J. Dudley, D. Brunner, A. Kokhanovskiy, S. Kobtsev, S. Turitsyn, Machine learning and applications in ultrafast photonics, Nat. Photonics 15 (2021) 91–101, https://doi.org/10.1038/s41566-020-00716-4.

[19] S. Yamashita, M. Nishihara, Widely tunable erbium-doped fiber ring laser covering both C-Band and L-Band, IEEE J. Sel. Top. Quantum Electron. 7 (1) (2001) 41–43, https://doi.org/10.1109/2944.924007.

[20] J. Nilsson, W.A. Clarkson, R. Selvas, J.K. Sahu, P.W. Turner, S.-U. Alam, A. B. Grudinin, High-power wavelength-tunable cladding-pumped rare-earth-doped silica fiber lasers, Opt. Fiber Technol. 10 (2004) 5–30, https://doi.org/10.1016/j.yofte.2003.07.001.

[21] D. Li, H. Jussila, Y. Wang, G. Hu, T. Albrow-Owen, R.C. Howe, Z. Ren, J. Bai, T. Hasan, Z. Sun, Wavelength and pulse duration tunable ultrafast fiber laser mode-locked with carbon nanotubes, Sci. Rep. 8 (2018) 2738, https://doi.org/10.1038/s41598-018-21108-3.