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Review

Methods Controlling Radiation Parameters of Mode-Locked All-Fiberized Lasers

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Abstract: Fibre lasers are distinct in that their optical train is decoupled from the environment, especially in the all-fibre format. The attractive side of this decoupling is the simplicity of maintenance (no need to align the cavity or keep the optical elements clean), but the flip side of this is the difficulty one encounters when trying to control the output parameters. The components used in all-fibre laser cavities are usually different from those of free-space laser cavities and require new approaches to control. Essentially, an important task emerges, i.e., research and development of all-fibre laser components able to adjust their parameters (ideally by electronic means) in order to tune key parameters of the output radiation—wavelength, output power, and so on. The present review analyses the existing methods of control over the output parameters of mode-locked all-fibre lasers. It is further noted that a method relying on several independently pumped active media may be promising in this regard.

Keywords: fiber laser; mode-lock; “all-PM-fibre” configuration

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1. Introduction

Fibre lasers bring a new level of convenience, and especially when implemented in the “all-PM-fibre” configuration [1], because there is no need to align the laser cavity or to keep clean the intracavity optical elements, there is no need to keep the ambient conditions very stable, and so forth. The obverse of this convenience, however, is the quite limited possibility of control over the output parameters of fibre lasers, particularly mode-locked fibre lasers (MLFLs) and particularly those with electronic control. Here, the output parameters of MLFL mean the key parameters—wavelength, power, duration and repetition rate of pulses, and so forth. The isolation of the fibre laser cavity design needs further development of new means (compatible with fibre-optical technologies) to control over radiation properties, which differ substantially from the traditional ones used in volumetric lasers. Since there is now a significant lack of such new methods, many fibre lasers are controlled with elements that have been well established in volumetric lasers and are adapted to fibre-optical technology by adding fibre input/output and a dust-proof (or evacuated) small package. Application of such elements in fibre lasers can scarcely be a subject of special study, and this is rather a technical or technological topic. We are more interested in specifically fibre-based methods of laser radiation control, which are found only or predominantly in fibre lasers. The additional condition imposed on these methods is that they should allow electronic control. Such methods need more development because the users expect from the new methods the same level of flexibility and convenience that became habitual when working with free-space lasers with discreet elements.

If one considers only fibre lasers with such methods of control, very often MLFL offer the sole adjustment parameter, the radiation power of one pump source. Because it is not possible to use only one parameter for the flexible adjustment of several output radiation parameters (including pulse duration, energy/power, wavelength, and pulse chirp), several controllable parameters are needed.

This overview is focused on methods of radiation parameter control in MLFLs with emphasis on the possibilities of electronic control. It should be noted that in spite of a relatively long history of MLFL development, there are practically no publications systematically studying the means of control over MLFL output parameters specific to fibre optical technology. In part, this is because such means (aside from the already mentioned pump power adjustment) only started emerging in recent years (both compatible with the "all-PM-fibre" configuration and electronically controllable). Correspondingly, there also emerged the need for the thorough study of these means at the current level of advancement and possibilities.

2. Mechanical Action on Fibre

Geometrical deformation of the MLFL cavity fibre by bending, stretching, compression, or torsion may be an efficient way of control over the output parameters of MLFLs (Figure 1), especially if the mechanical action is aimed at a Bragg grating (BG) recorded in the fibre rather than the fibre itself. One demerit of mechanical methods, similar to controlling MLFL parameters by temperature variation, is relatively slow response and the need to make sure that the fibre deformation does not become irreversible.

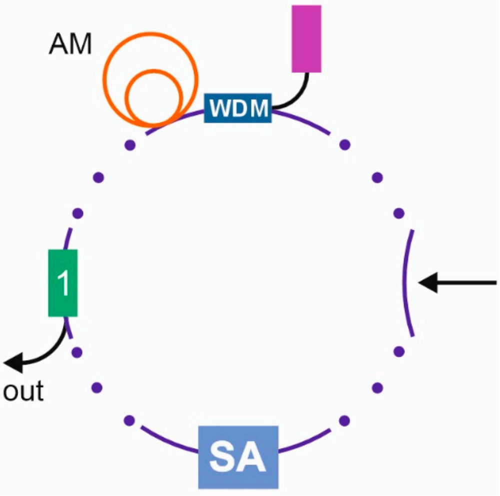

Figure 1. General scheme of mode-locked fibre laser with mechanical action on fibre: SA—saturable absorber (material or artificial); AM—active medium; and 1—coupler.

The possibility of fibre bending as a method of controlling the parameters of radiation propagating inside is a well-known fact [2]. In particular, fibre-optical polarisation controllers (based on bending and torsion of fibre [3]) are used both for triggering passive mode-locked operation [4] and for control over the output parameters of MLFL 9 (see, for instance, [5,6]). Other problems of action of a three-paddle manual polarisation controller on fibre are that a particular setting is virtually irreproducible and, additionally, has a drift that necessitates periodic re-tuning. If we add to that the instability of ambient parameters (air temperature and pressure, and so on), it may be necessary to re-tune such a controller fairly frequently.

By bending, stretching, or compressing a fibre with a BG written into it, one can tune the radiation wavelength within broad ranges [7]. High sensitivity of parameters (such as wavelength, polarisation, mode composition, etc.) characterising radiation passing through the fibre BG to its response to mechanical action is also used in the opposite direction for sensing [8].

It must be noted here that the amount of mechanical force applied to the fibre is limited by the requirement that the resulting deformation be elastic, i.e., reversible. Additionally, instead of fibre or fibre BG, mechanical action may affect, for example, a cavity mirror [9]. The electrostatically actuated micro-mirror used in [9] played at the same time the role of the cavity Q-switch.

3. Temperature Adjustment of MLFL Cavity Elements

Temperature adjustment of MLFL cavity elements is an obvious approach to remotely modify their parameters (Figure 2). The advantage of this method is the possibility of electronic control of heating and temperature stabilisation, and the drawbacks are slow response time and the need of thermally isolated spaces around the controlled elements. Aside from this, controlling the temperature of MLFL elements does not allow adjustment of MLFL radiation parameters in a broad range. However, this last statement is not universal: temperature sensitivity of various MLFL elements may be different, and some of them may be controlled fairly efficiently. First, let us consider the temperature dependence of the properties of the cavity fibre itself. Its chromatic dispersion is the most temperature-sensitive parameter [10–15]. Within a modest range of temperature excursion (e.g., −10 °C to +50 °C), the chromatic dispersion variation is also relatively small and amounts to 0.0003–0.004 (ps/nm/km)/°C. Correspondingly, adjustment of the fibre temperature within a small range does not affect chromatic dispersion significantly. Nevertheless, the temperature adjustment range may be substantially expanded into positive values up to ~+1000 °C (silica glass does not suffer deformation up to 1000 °C) and into negative values down to ~−270 °C [16]. As the temperature excursion range was broadened (from 20 °C to 420 °C), the measured shift of the zero-dispersion wavelength was found to be 0.02 nm/°C [15]. Temperature dependence of chromatic dispersion and the zero-dispersion wavelength are fairly weak, and to change them significantly, the temperature must be varied in even broader ranges and/or longer fibre must be used.

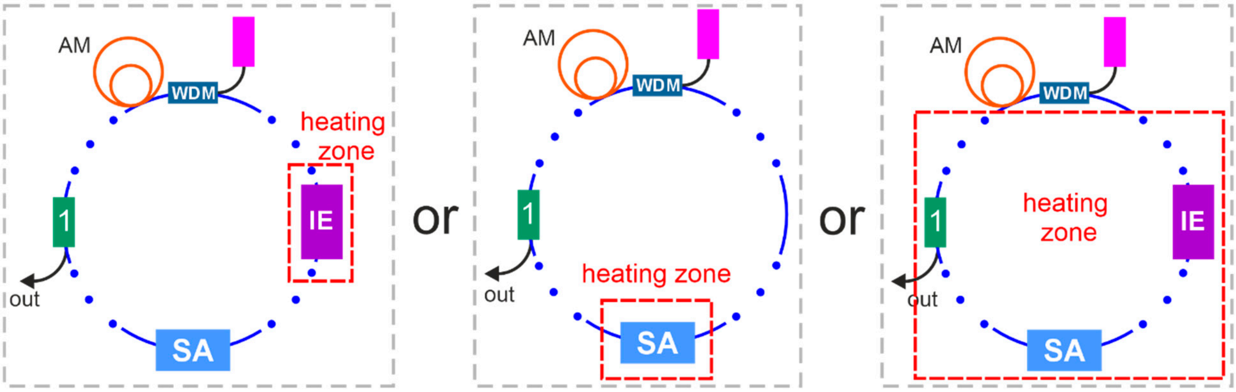

Figure 2. General scheme of mode-locked fibre laser with temperature adjustment: SA—saturable absorber (material or artificial); AM—active medium; IE—intracavity element; and 1—coupler.

It is more efficient to vary temperature of fibre Bragg gratings (FBG) [17]. Temperature expansion/contraction of the fibre material leads to the modification of the grating period, which, in its turn, shifts the spectral position of the grating reflection peak [17,18]. The typical magnitude of change lies within ~12–14 pm/°C (around 1.55 µm) [19,20]. This sensitivity may be improved significantly (by a factor of 4–5), for example, through the use of an external conduit with a larger coefficient of thermal expansion [21]. High thermal sensitivity of the transmission/reflection spectrum of FBG makes it possible not only to control the fibre laser parameters by adjustment of the FBG temperature, but also to use FBG as a high-precision temperature sensor [22].

It may be possible to use the temperature dependence of some physical effect (for instance, the Kerr effect [23]) not for controlling the laser's output parameters, but for changing the temperature or electrical field strength.

Another element whose properties may significantly change over a temperature range is a saturable absorber. Temperature sensitivity of this element's properties was demonstrated in [24].

Heating/cooling of other elements of a fibre laser cavity (WDM combiners/dividers, couplers, isolators, etc.) only affects weakly the optical properties of these elements. Therefore, in practice, their properties are not adjusted by temperature variation.

A certain temperature profile is necessary when the mechanism of nonlinear polarisation evolution is used [4] for mode locking of the laser radiation. The evolution of radiation polarisation within the fibre depends, among other things, upon the fibre temperature. Hence, for maintaining mode-locked operation of a fibre laser by this method, the fibre temperature must be stabilised.

Other ambient parameters (air humidity, pressure) affect comparatively weakly the properties of the fibre laser elements. However, specially designed elements (D-shaped/no-core fibre or micro-cavities, etc.) may be more sensitive to these parameters [25–28]. It should be mentioned that controlling fibre laser parameters by variation in humidity or ambient pressure is not practically used.

Furthermore, variation in magnetic or electric field for controlling output parameters of fibre lasers is also not used, even though fibre lasers are actually used as sensors of these fields [29,30]. Although, instead of the natural fibre sensitivity to these fields, that of the material (e.g., modulator piezo-element and so on) used in a quasi-fibre component (a volumetric element with fibre-optical input and output) may be relied upon [29].

4. Controlling Output Parameters of MLFLs with Two Pump Sources

This method may be applicable when changing the ratio of the pump source powers may extend the range of control and/or the number of adjustable MLFL parameters or may even modify the MLFL generation regime. This method is attractive because the pump sources may be electronically controlled, particularly in the “all-fibre” configurations. For control, one may use relatively inexpensive semiconductor pump lasers, which may be well integrated into fibre-optical systems (fibre-coupled output and wavelength division multiplexing fibre device). Its application is especially effective in combination with artificial saturable absorbers [31] based on NOLM/NALM [32–35]. Placing the pump sources either in the same NALM ring or in different rings of the Figure 3 cavity (Figure 3) improves the flexibility of control over the output laser parameters. Adjustment of the ratio of the pump source input powers allows compiling a map of generation regimes [36] that usually spans three distinct regimes: continuous wave, noise-like pulse [37,38], and generation of conventional unstructured pulses. If the laser cavity uses polarisation-maintaining fibre and other elements, the generation map is reliably reproducible and can be used not only for the selection of the generation regime but also for choosing a regime with desirable pulse parameters. The main disadvantage of the method is that the desired pulse parameters may be only reachable at pumping powers below the maximum, thus reducing generation efficiency. This is why this method cannot be called perfect. Furthermore, it does not allow substantial tuning of the output wavelength. Among the advantages of this approach are compatibility with electronic control, all-fibre configurations, and the good scaling. Using a greater number of pump sources for controlling the output parameters of MLFLs may become a promising field of development because pumping laser diodes are relatively inexpensive and long-lasting.

It is important to emphasise that the smooth adjustment of the ratio between the powers of the two pumping sources does not always correspond to a continuous change in some radiation parameter. Nevertheless, this method allows in some way (either continuously or discretely) changing the parameters of the generated pulses.

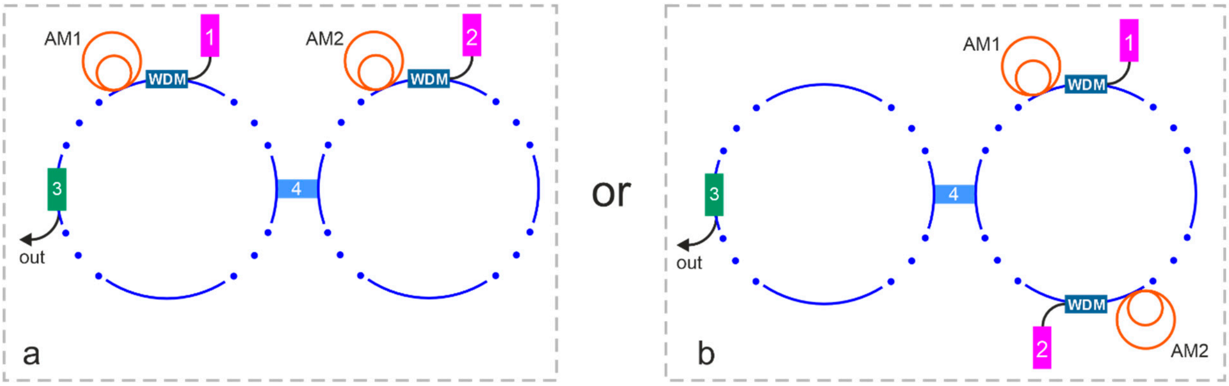

Figure 3. General scheme of mode-locked fibre laser with two pump sources: AM1;2—active media; 1;2—pump lasers; 3—coupler 1; and 4—coupler 2; (**a**)—active media in different resonator rings, (**b**)—active media in the same resonator ring.

5. Controlling the Output Radiation Parameters of MLFLs through Adjustment of the Material-Based Absorbers

Most implementations of material-based saturable absorbers in fibre lasers do not provide for any adjustment of any absorber property during operation. Such absorbers are secured between fibre ferrules or deposited on the end facet of the fibre/ferrule or interact with the cavity radiation through side-polished/tapered fibre. Normally, the conditions of interaction between the radiation and the absorber remain fixed, even though they may be altered manually (by variation in the fixation pressure). Nevertheless, certain types of material-based saturable absorbers allow the electrical control of their properties. Consequently, this makes them amenable to electronic control of the generated pulse parameters. In particular, such control is possible with semiconductor-based saturable absorber structures [39,40] (Figure 4).

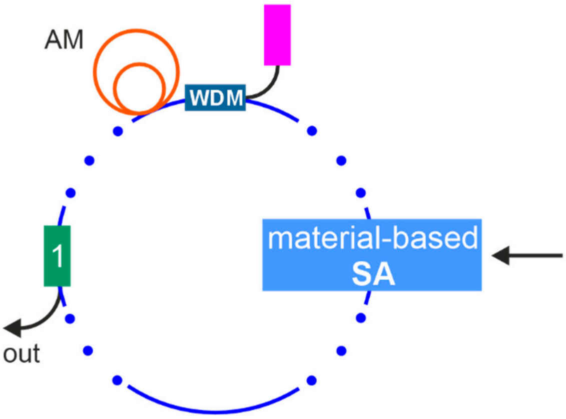

Figure 4. General scheme of mode-locked fibre laser with adjustable material-based absorbers: AM—active medium; 1—coupler.

It must be mentioned here that non-semiconductor material-based saturable absorbers may be also electrically controllable (such as graphene-based super-capacitors [41–43]), and not only in the free-space configuration, but also in the "all-fibre" format [44,45]. Moreover, the "all-fibre" format was demonstrated for variation in the properties of a graphene saturable absorber driven by separate optical radiation [46,47]. Essentially, this is equivalent to electronic control. A different approach was demonstrated in [48–50] where it is shown that an ionic liquid in contact with a carbon-nanotube saturable absorber (CNSA) may provide electrically driven control over the CNSA properties by the application of voltage to the ionic liquid.

As it is demonstrated, electronic control over the parameters of material-based saturable absorbers is possible. It does not, however, solve their major problem, a limited lifetime [51,52], which is substantially shorter than that of other components in a fibre laser cavity. Artificial saturable absorbers [53] deliver far better lifetime, but other methods are necessary to control their parameters.

6. Controlling Output Parameters of MLFLs with Modified Fibres

Another way of action on radiation propagating down the optical fibre core and fully contained inside is a modification of the fibre that allows the radiation in the core to partially spread outside (for example, as an evanescent field: D-shaped fibres [54] or tapered fibres [55,56]). Fibre modification technologies may include side polishing [57,58], chemical [59] or CO_2 laser etching [60,61], femtosecond laser-induced water breakdown [62], or D-shaped fibre drawn from D-shaped preforms [63], or arc-shaped fibre [64], or others. Furthermore, for affecting the radiation in the fibre core, the corresponding modifications may be made directly to the core: it may be local or periodic changes in the core refractive index by UV radiation [65,66] or by ultra-short laser pulses [64], introduction directly into the core of some material through a microscopic hole in the fibre [67], or formation of a micro-cavity inside the fibre [68]. Additional optical action on the fibre core may be created by a V-groove [69].

Nevertheless, these methods, in their majority, do not allow dynamic control over output parameters of MLFLs; the interaction of radiation with introduced objects inside or close to the core is stationary. Rare exceptions are those objects (substances) whose properties may be changed by electric signals [48–50].

7. Controlling Output Parameters of MLFLs by Radiation Selection: Spectral, Amplitude, Polarisational, and Temporal

This type of control implies the presence in the cavity of an element that can be electrically driven to modify the spectrum, intensity, and polarisation of MLFL output. A recent review [6] analyses the methods of electronic control over the generation wavelength(s) of MLFL. Variation in the radiation intensity may be implemented both with the adjustment of the pump power fed into the active medium (relatively fast changes may be introduced if the active medium is a semiconductor optical amplifier [70]) or when using radiation intensity modulators [71] (electro-optical, acousto-optical, and others). It must be noted that there are a variety of approaches to adjusting the MLFL radiation intensity. Modulation of the radiation polarisation can also be implemented [72]. A more complex mechanism of electrically driven polarisation control using liquid crystal phase plates was demonstrated in [73]. Application of liquid crystals for the control of MLFL radiation polarisation is known for a long time [74]. However, this method is only feasible at relatively low output power of the laser that does not cause excessive heating or photo-darkening of the liquid crystal. Spatial light modulators [75] allow modification not only of the radiation spectrum, but also of the temporal properties of MLFL pulses. The drawback of this method is that it is not compatible with the “all-fibre” format. For the same reason and because electrical control is not possible, passive radiation intensity filters are rarely used [76]. Spectral filters with variable transmission bandwidth may have fibre-optical input and output [77], and also may be electrically driven [78], but they are used infrequently in their simple configurations (as a free-space component without electrical control [79]). A promising solution compatible with the “all-fibre” format and allowing electronic control was proposed in [80]: wavelength tuning in the range exceeding 40 nm around 1.5 μm was achieved by temperature adjustment from 23 °C to 100 °C of a system consisting of three Bragg gratings with different periods. For selection of MLFL radiation, some exotic components may be used, such as optofluidic chips [81] or micro-fibre [82].

8. Intellectual Technologies for Controlling MLFL Radiation Parameters

This approach relies on the assumption that it is possible to use machine learning methods (or artificial intelligence, neural networks, etc.) in order to make a fibre laser generate radiation with pre-determined (or improved) parameters. Here, the output data are radiation parameters (in the case of short pulses, it will be spectrum, duration, energy, and pulse structure), whereas the input data are the pumping radiation power and other control parameters described earlier. The objective of intellectual technologies is the identification of complex dependencies between the input and output data [83–90].

The general problem of this approach is that acquisition of the output parameters requires measurement equipment (auto-correlator, spectrum analyser, and so forth), whose cost may exceed that of the laser. Careful identification of radiation pulse parameters is also important because diverse generation regimes may exist in one and the same laser [91,92]. Comprehensive definition of the output data, as well as their sufficient amount, are the pre-requisite for the successful application of artificial intelligence algorithms. Only being able to detect the presence of a pulsed generation is not adequate for the unambiguous determination of the generated pulses. Consequently, the weak spot of the intellectual methods is the need of data about the output pulse parameters, which is acquired by complex equipment that effectively becomes an integral part of the laser. This poses additional onus on the users: they have to be proficient in working with this equipment.

Therefore, adoption of intellectual technologies entails extra costs and efforts. There is no clarity about the net advantage because fibre lasers with output parameters meeting the users' expectations may be also implemented without intellectual technologies.

The main advantages and drawbacks of the methods discussed so far are summarised in Table 1.

Table 1. The main advantages and drawbacks of controlling methods.

№	Control Method	Advantages	Disadvantages
1	Mechanical action on fibre	Simplicity, possibility of implementation in practically any conditions	Slow response time, repeatability problems, possible lack of parameter reproducibility due to plastic deformation of the fibre
2	Temperature adjustment of MLFL cavity elements	Simplicity, possibility of electronic control	Slow response time, need of thermally isolated spaces
3	Controlling output parameters of MLFL with two pump sources	Fast response time, possibility of electronic control	Desired pulse parameters may be only reachable at pumping powers below the maximum
4	Controlling the output radiation parameters of MLFL through adjustment of material-based absorbers	Certain types of material-based saturable absorbers allow electrical control of their properties	Limited lifetime of material-based absorbers, difficulties in controlling the properties of absorbers
5	Controlling output parameters of MLFL with modified fibres	Great variety of methods, possibility of electronic control in rare cases	Methods, in their majority, do not allow dynamic control over output radiation parameters
6	Controlling output parameters of MLFL by radiation selection: spectral, amplitude, polarisational, and temporal	Fast response time, use of components adapted to the all-fibre format	Needs intracavity elements allowing adjustment (electronic or manual) of their parameters.
7	Intellectual technologies for controlling MLFL radiation parameters	Many laser tuning functions may be automated	Acquisition of the output radiation parameters requires complex measurement equipment

9. Conclusions

The analysis of methods used to control the parameters of radiation pulses generated by mode-locked fibre lasers shows that one of the promising approaches may be control through laser diodes pumping independent active media (Figure 5). Such control may be electronic and relatively inexpensive to implement. Another advantage of this method is its compatibility with the “all-fibre” format. Two laser diodes independently pumping two active media may modify the parameters of an artificial saturable absorber [34] or the laser as a whole [36]. It has been already demonstrated that, in principle, broad-range tuning of the output wavelength of a mode-locked fibre laser is possible through adjustment of the pump radiation power [93]. This method may be further developed by implementation in a cavity with an artificial saturable absorber. Control over other radiation parameters (for instance, the radiation spectral width and so on) via local changes in intracavity gain so far has not been demonstrated. But controlling these parameters with additional laser diodes could further develop the idea of using several pumping laser diodes to control output parameters of a mode-locked fibre lasers and thus achieve a certain uniformity in doing this. One obvious advantage of this control method is the possibility of electronic implementation, relatively low cost, and compatibility with the “all-fibre” or “all-PM-fibre” format.

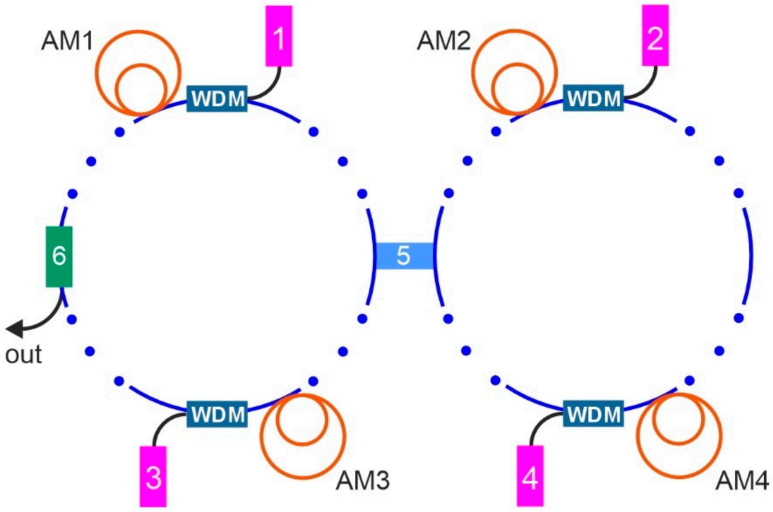

Figure 5. Concept of electronic control over parameters of a mode-locked fibre laser: 1–4—pumping semiconductor laser diodes; 5—coupler 1; 6—coupler 2; and AM1–4—active media.

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