Mode-locked long fibre master oscillator with intra-cavity power management and pulse energy > 12 μJ

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Abstract: Combined lengthening of the cavity of a passive mode-locked fibre master oscillator and implementation of a new concept of intra-cavity power management led to achievement of a record-high pulse energy directly at the output of the mode-locked fibre master oscillator (without any subsequent amplification) exceeding 12 μJ. Output powers at the level of > 12 μJ obtainable from a long-cavity mode-locked fibre master oscillator open new possibilities of application of all pulse types that can be generated in such oscillators.

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1. Introduction

The principle of considerably raising the pulse energy of passive mode-locked fibre master oscillators (‘dissipative soliton fibre lasers’ [1]) due to greatly lengthened oscillator cavity [2] has resulted in relatively high pulse energies in the vicinity of several μJ directly at the output of the master oscillator at the resonator length in the range of 1–25 km [3–6]. Various master oscillator configurations were tested having both normal and anomalous total cavity dispersion. Nevertheless, in none of the studied cavity layouts the output pulse energy exceeded at most few μJ. In [2], the obtained pulse energy amounted to 3.9 μJ at the cavity length of 3.8 km, and subsequent attempts at raising the output pulse energy further by elongation of the cavity first to 8 km [4] and then to 25 km [5] only led to proportionally lower average radiation power at which a stable mode-locked operation was still possible. The average radiation power had to be reduced because higher peak pulse power in longer resonators resulted in unstable mode locking due to nonlinear effects, in particular Raman-driven destabilisation [7]. Therefore, the pulse energy rose with the resonator length up to a certain limit value (4 μJ [4,5]), after which it saturated: longer cavities required lower average radiation power for stable mode locking. Consequently, the maximal achievable pulse energy in a passive mode-locked long fibre oscillator was capped at 4 μJ and stayed at this level for approximately the last 7 years [2].

The present work for the first time breaks this limit and reports pulse energy exceeding 12 μJ directly at the output of a mode-locked Yb-based long fibre oscillator. This significant rise in pulse energy became possible owing to a new approach to cavity design of fibre master oscillators: we implemented a specially crafted layout, which distributed the intra-cavity radiation so as to maintain lower radiation power in the long part of the cavity, thus minimising nonlinear effects in the long fibre. Additionally, instead of the previously used mode locking mechanism based on nonlinear polarisation evolution (NPE), in this work we relied on a nonlinear amplifying loop mirror (NALM) [8]. Combining these two new approaches to design of passive mode-locked long fibre master oscillators resulted in pulses with energy of 12.4 μJ at the output of the oscillator.

It must be noted that the duration of pulses generated in long cavities of mode-locked fibre master oscillators falls into the nanosecond range, while the pulse repetition rate in the fundamental mode locking regime amounts to tens or hundreds of kHz. Pulse parameters of mode-locked long fibre master oscillators are close to those of Q-switched fibre lasers. Nevertheless, pulses generated in these long mode-locked lasers possess certain distinctive features. For example, long fibre master oscillators mode-locked due to NPE or by nanotubes produce pulses, which may exhibit giant chirp [9,10] and may be consequently compressed by a factor of up to ~100 [11] or at least to a fraction of their initial duration in the case of transient pulses [12]. Transient and noise-like (‘double-scale’ [13]) pulses may be also very interesting for applications due to their specific internal structure [14] and high peak power which results in high efficiency of nonlinear transformations [15,16].

Another salient feature of pulses generated in mode-locked regimes is that their repetition rate does not depend on the radiation power, unlike that of pulses generated in passive Q-switched fibre lasers [17]. In the majority of implementations, duration of pulses generated in passive mode-locked fibre lasers depends much less on the radiation power than it does in passive Q-switched fibre lasers [17,18].

Therefore, pulses produced in passive mode-locked fibre master oscillators exhibit certain peculiarities, which may be useful in various applications. Higher available energy of such pulses is in demand and effectively broadens the area of their potential applications.

2. Experiment

The experimental set-up used in the present work is schematically shown in Fig. 1.

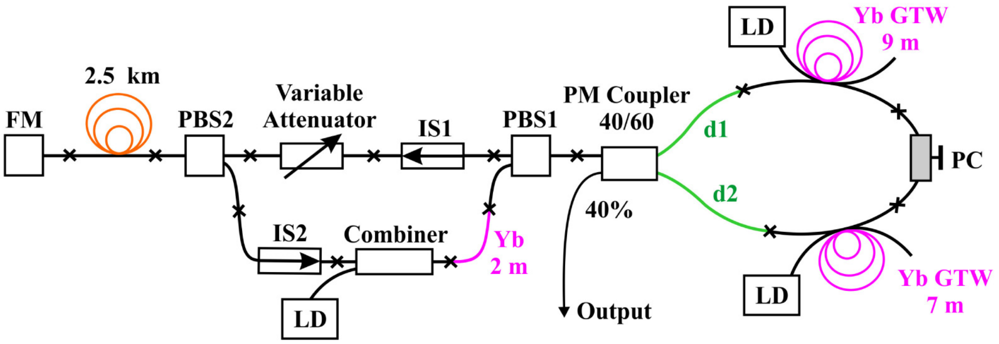

Fig. 1. Schematic diagram of the experimental set-up: LD – pumping laser diode, PC – fibre polarisation controller, PBS – fibre polarisation beam splitter, FM – fibre Faraday mirror, IS – fibre isolator, d1 and d2 – PM fibres.

The laser cavity is composed of a linear and a ring-shaped arms, the latter one laid out as a NALM and containing non-polarisation-maintaining fibre and two stretches of polarisation-maintaining fibre (d1 = 80 cm, d2 = 90 cm) which, together with the fibre-based polarisation controller, form a fibre birefringent spectral filter [19]. As it was earlier demonstrated in [20], spectral filtration of radiation in a normal-dispersion fibre laser cavity improves stability of passive mode-locked lasing, allowing generation of pulses with greater energy. The gain section of NALM includes two (7- and 9-m long) active side-pumped Yb-doped fibres (GTWave fibre design explained in [21]) each with its independent pump. Their absorption of the pump radiation at 980 nm was 3.9 dB/m. The 7-m long fibre was pumped with 3.5 W, while the other one received 4.5 W. Adjustment of the pump intensity ratio makes it possible to control the phase incursion difference of the two counter-propagating waves in the NALM. This adjustment not only ensures stable operation of the laser at different output radiation power levels, but also allows to trigger mode locking at relatively low generated radiation power. The ring section of the cavity is connected to the linear one through a polarisation-maintaining (PM) fibre coupler with 40/60 ratio (the 40% port is used to couple the radiation out of the laser).

The linear arm of the laser cavity consists of two direction-split linear segments placed between two fibre polarisation beam splitters, 2.5-km fibre stretch for cavity elongation, and a Faraday mirror at its opposite end.

Mode-locked operation is triggered at a certain pumping power ratio between the two active fibres in the NALM, the total (both sources) pumping power threshold amounting to 3 W. The polarisation controller is not used for starting mode-locked operation, its function

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being only to control the transmission bandwidth of the fibre-based birefringent filter. Although the cavity contains non-PM fibre spans, polarisation-sensitive elements and a polarisation controller, we believe that our laser is not appreciably affected by nonlinear polarisation evolution [22] because after mode-locked operation is established, it cannot be disrupted by adjusting the polarisation controller settings.

After mode locking is established, radiation pulses move along the cavity in the following manner: upon exit from the NALM, they are fed through the 60% port of the PM coupler into the split section of the linear cavity arm where they are direction-split at PBS1 and once again combined at PBS2. The propagation direction of radiation in the split section of the cavity is determined by optical isolators IS1 and IS2. The upper branch (Fig. 1) is taken by pulses going away from the NALM, while the lower branch is used to pass those moving towards the NALM. The split section of the linear cavity arm with a variable attenuator in the upper arm is used to lower radiation power in a 2.5-km-long fiber section. Correspondingly, the power of the radiation passing through the lengthening fibre becomes several times as low as that of the radiation inside the NALM, thus considerably reducing nonlinear effects in the cavity-lengthening fibre. A Faraday mirror at the end of the cavity's linear segment [23] serves to eliminate all the fluctuations in the linear birefringence of the cavity-lengthening fibre, including temperature- and pressure-induced ones. Upon the return pass through the 2.5-km fibre, the radiation pulses are fed into the lower branch of the split section, which contains one of the pumped active fibres. This restores the radiation power to the level it had upon exit from the NALM.

Therefore, the proposed laser resonator establishes two zones with significantly different intra-cavity radiation power: NALM zone with relatively high intra-cavity radiation power and the cavity-lengthening zone with relatively low radiation power. The NALM zone ensures high output radiation power, while the cavity lengthening zone reduces the pulse repetition rate. As a result, this composite-cavity master oscillator produces output pulses with relatively low repetition rate (41.7 kHz) featuring record-high energy of 12.4 μJ (which corresponds to the laser's average output power of 520 mW).

By analogy to dispersion management [24,25] and nonlinearity management [26], the proposed laser configuration for the first time implements intra-cavity power management allowing different intra-cavity radiation power in different parts of the laser cavity.

Figure 2 demonstrates the temporal envelope of the generated pulses recorded at 40-ps resolution with a photo-detector and a storage oscilloscope. The measured pulse duration was 4.3 ns, the central generation wavelength 1078.9 nm, and the spectrum FWHM (Fig. 2 c) was 0.06 nm without any sidebands. Spectrum width of 0.06 nm corresponds to coherence time of 25–28 ps, which is unusually long for stochastic filling of double-scale pulses. However, the question about internal structure of such pulses and their compressibility will be the subject of separate study.

It must be pointed out that the proposed laser layout requires only two pump sources for its operation: the first one in the NALM and the second one between the NALM and the cavity-lengthening fibre. The first of these sources ensures proper functioning of the NALM, while the second provides intra-cavity power management.

Let's estimate how the proposed intra-cavity power management solution opens a new way for pulse energy scaling. As the laser cavity length L increases, an approximately linear corresponding growth of the duration of the generated pulses T may be expected due to increasing laser cavity dispersion, $T \sim L$. It is necessary to limit nonlinear effects in order to ensure stable mode locking: $\int \gamma P(z)\, dz \leq \varphi_{max}$, where $P(z)$ corresponds to the distribution of the radiation power along the cavity, γ – nonlinear coefficient, φ_{max} – critical nonlinear phase incursion. This limitation suggests that the power of the generated pulses P should drop inversely proportional to the cavity length: $P \sim 1/L$.

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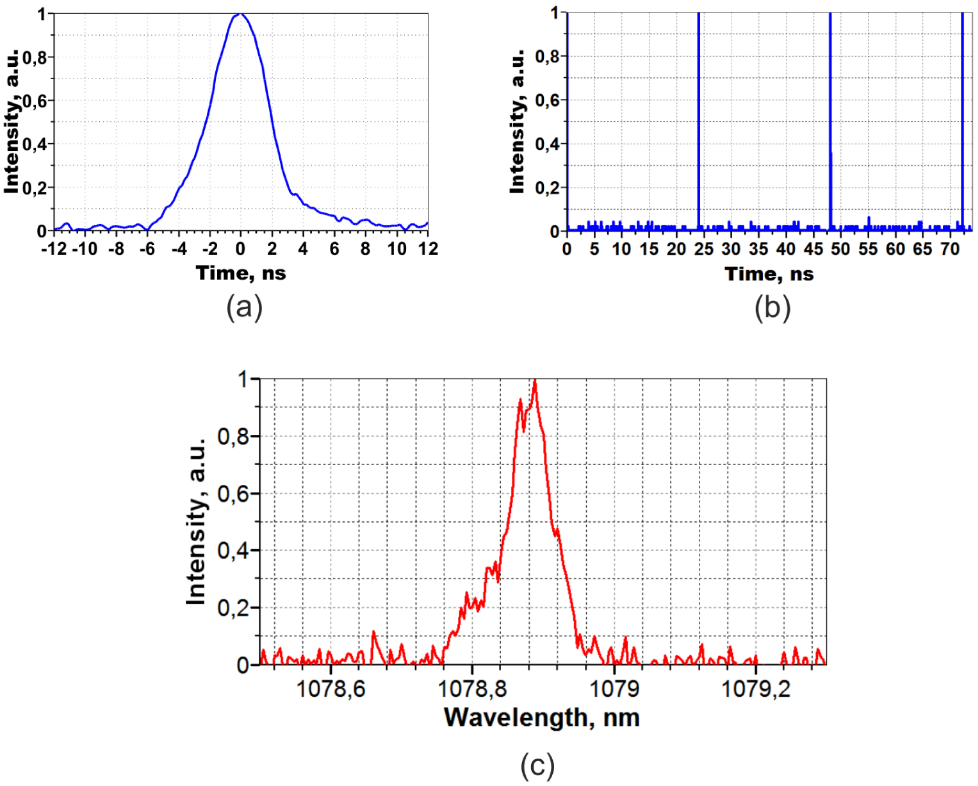

Fig. 2. Pulse operation of the fibre master oscillator. (a) Temporal pulse shape. (b) Oscilloscope trace of the typical laser output. (c) Pulse spectrum measured.

Therefore, we have the value of the pulse energy: $W \sim T \times P \sim L \times L^{-1}$ ~const, which is what was actually observed during the preceding experiments [2–5]. The new configuration proposed in the present work consists of two arms with different length ($L_1 << L_2$) having different radiation power level inside them ($P_1 >> P_2$). Consequently, for nonlinear phase incursion we obtain: $\varphi_{NL} = \int\gamma_1 P_1(z)\,\mathrm{d}z + \int\gamma_2 P_2(z)\,\mathrm{d}z \le \varphi_{max}$. For a basic estimate, let's take $\gamma_1 = \gamma_2$, $P_1(z) = P =$ const, $P_2 = P/a$, where a is the coefficient of signal attenuation within the second arm of the cavity. Then, we have $\varphi_{NL} = \gamma P \times (L_1 + L_2/a) \le \varphi_{max}$. Therefore, we can derive the expression for pulse energy scaling due to the second fibre segment (with low nonlinearity) added to the cavity:

$$k_W = \frac{W}{W_0} \approx \frac{PT}{P_0 T_0} \approx \frac{L_1 + L_2}{L_1 + L_2/a} \tag{1}$$

Coefficient k_W represents the ratio of energy W of pulses generated in the cavity containing a lengthening fibre L_2, to the corresponding energy W_0 observed in a cavity of length L_1. At $L_2 = 0$ or $a = 1$ we have $k_W = 1$. In the limiting case of $L_2 >> L_1$ and $L_2 / a >> L_1$, we obtain $k_W \sim a$. This means that the proposed intra-cavity power management approach in long cavities of mode-locked fibre master oscillators leads to enhancement of the output pulse energy in the vicinity of the value of the attenuation of the radiation power within the cavity-lengthening fibre L_2. Thus, output pulse energy in significantly lengthened cavities of mode-locked fibre lasers may be enhanced by roughly the same factor as the energy inside the cavity-lengthening fibre is reduced.

There are two possible fundamental limitations of output energy enhancement by intra-cavity power management in passive mode-locked long fibre master oscillators:

a) substantial absorption of radiation in the cavity-lengthening fibre;

b) pulse repetition period reaching values comparable to the upper state lifetime of the active medium of the laser (~1 ms for ytterbium-doped silica fibres [27]).

In the studied laser, the pulse repetition period amounted to 24 μs. Accordingly, it is likely possible to slow down the pulse repetition by more than an order of magnitude before limitation b) kicks in. Such cavity elongation (by more than an order of magnitude) is also possible if the cavity-lengthening fibre with relatively low losses at the generation wavelength is chosen (*e.g.* with attenuation not exceeding 0.5 dB/km). In such a case, it is not unreasonable to expect pulse energies at the output of a passive mode-locked long fibre master oscillator reaching 100 μJ and even higher. One of the probable technical obstacles to achievement of ultra-high pulse energies directly at the output of a fibre master oscillator is limited radiation damage threshold of the employed fibre components.

3. Conclusion

The present work for the first time demonstrates that record-high pulse energies exceeding 12 μJ can be obtained directly at the output of passive mode-locked Yb-based long fibre oscillator without resorting to additional fibre amplifiers. Mode locking was implemented with the help of a nonlinear amplifying loop mirror, while nonlinear effects in a 2.5-km cavity-lengthening fibre were substantially reduced through a specially designed master oscillator layout, in which intra-cavity radiation power may be significantly different in different parts of the cavity. The developed layout using an intra-cavity power management solution, which is proposed here for the first time, opens prospects of further pulse energy enhancement in passive mode-locked long fibre master oscillators (reaching 100 μJ and higher), which was only limited in the present work by the available pump power and the length of the used fibre.

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