Mode-Locking in 25-km Fibre Laser

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Abstract *We demonstrate mode-locking and single-pulse generation in fibre laser with 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 pulse energy of 3.7 μJ.*

Introduction

The length of the laser resonator is 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. Different techniques such as Q-switching, cavity dumping and optical amplification are currently used to generate high energy pulses. 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.

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 [1] and with fibre [2, 3] lasers. The reduction of the pulse repetition rate by the order of magnitude down to a few MHz scale and the correspond-ing 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 [4, 5] 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 [6-10]. 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 [5].

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. Therefore, substantial increase of the cavity length in fibre mode-locked laser is a significant fundamental and experimental challenge.

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.

Experiential setup and results

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

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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.

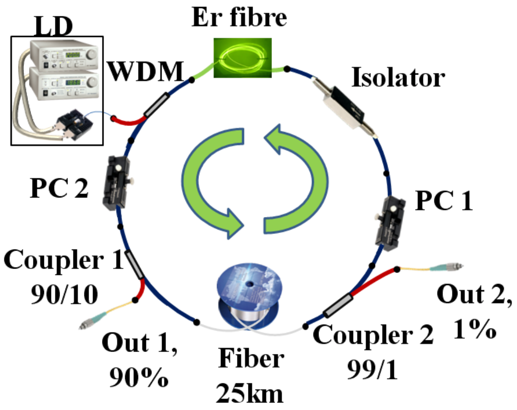

Fig. 1: Schematic depiction of the 25-km long ring fibre laser design.

The output power was taken out through a 90/10 fibre coupler placed before 25-km fibre. Using only 10% of the radiation power in the feedback we reduced the nonlinear effects in the 25 km of fibre and achieved a more sustained mode-locking. 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 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 7 ns, respectively.

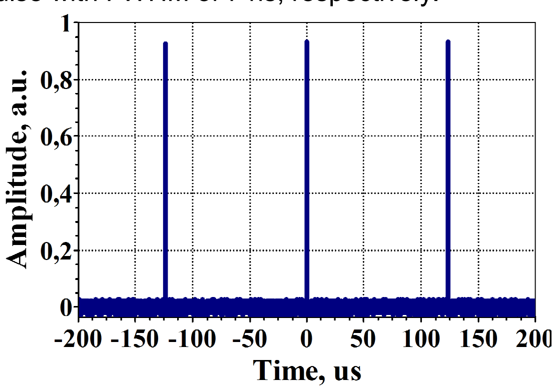

Fig. 2: Measured comb of pulses with a mode-locking repetition rate $T_R=nL/c \approx 123{,}5$ μs

The train of pulses has a period of 123.5 μs which corresponds to a 8.097 kHz repetition rate. 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.

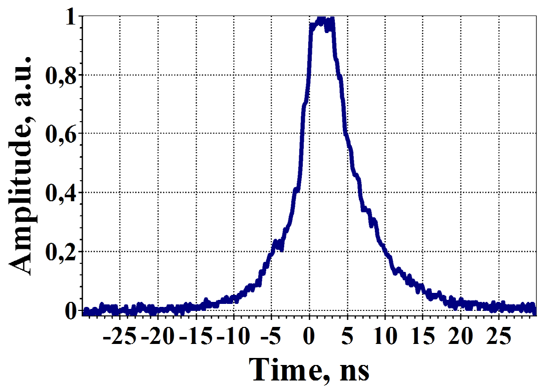

Fig. 3: Temporal profile of the generated pulse measured at the output 1.

As the laser operated in the near-threshold regime (small pump power and using only 10% power for the feedback), the noise level in the optical spectrum (Fig. 4) is associated with spontaneous-emission spikes.

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 [10] with total laser resonator length shorter by factor of 20 (1.25 km).

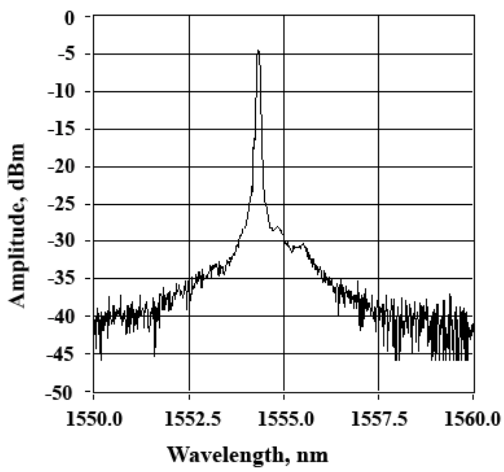

Fig. 4: Spectrum of a generated pulse.

Disscussion

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 [11-14]. Note that no special narrow band filter limiting laser radiation spectrum was used in a stable mode-locked operation, unlike the regimes reported in [15]. 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.

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 non-usual ones with increase of laser cavity length is already demonstrated and discussed in [16]. Therefore, we believe that our results might open a new research area of ultra-long mode-locked lasers.

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