Quantum Electronics **51** (12) 1061 – 1067 (2021)

https://doi.org/10.1070/QEL17653

Generation of high-energy single pulses and pulse clusters in ytterbium fibre lasers with quasi-synchronous modulation of the pump power

A.V. Ivanenko, B.N. Nyushkov, S.V. Smirnov

Abstract. **Additional capabilities of the method of quasi-synchronous pump power modulation developed by the authors for nanosecond high-energy pulsed oscillation of fibre lasers with a long-lived (about 1 ms) upper laser level are investigated. Using an Yb fibre laser as an example, it is shown that quasi-synchronous pump power modulation makes it possible to generate not only a periodic sequence of single nanosecond pulses, but also regular pulse clusters with a controlled number of nanosecond subpulses that make up a cluster. In addition, the feasibility of scaling the energy of laser pulses obtained by the method of quasi-synchronous modulation of the pump power is studied when proceeding to the use of active double-clad fibres and higher-power multimode pump sources. Pulses with energies up to 430 nJ are obtained in a laser configuration maintaining linear polarisation of radiation. The results obtained significantly expand the possibilities of applying the method of quasi-synchronous modulation of the pump power in conventional fibre lasers based on stimulated emission.**

Keywords: *fibre lasers, quasi-synchronous modulation of the pump power, pulse clusters.*

1. Introduction

Synchronous pumping of lasers is an energy efficient and relatively simple method for obtaining pulsed lasing, which can be associated with active mode locking. Such pumping has found its application in various types of lasers, primarily in semiconductor lasers [1], liquid dye lasers [2], and some types of bulk solid-state lasers [3]. Synchronous pumping is also widely used in hybrid lasers with a fibre resonator and a semiconductor active medium [4, 5], as well as in Raman fibre lasers [6, 7]. However, the use of synchronous pumping in conventional stimulated emission (SE) fibre lasers has been highly limited until recent time. The direct use of synchronous pumping in lasers with such inertial active media as Yb- or Er-doped fibres (characterised by a much slower gain recovery in comparison, e.g., with a semiconductor optical amplifier), seemed ineffective from the point of view of producing short and ultrashort pulses. In addition, the classical approach to the implementation of synchronous pumping in such lasers in order to form extremely short pulses would require fast ($\tau \leqslant 1$ns) and deep (close to 100 %) modulation of sufficiently high-power pump laser diodes, which is a technically difficult task. Therefore, until recently, synchronous pumping was realised only in less inertial Tm-doped fibre lasers using complex pump sources consisting of a pulsed (or modulated) master oscillator and a separate power amplifier [8, 9].

Only recently, we have proposed [10] and investigated [11] a new approach to synchronous pumping of conventional fibre lasers with SE, which allows significant simplification of its technical implementation and the formation of extremely short laser pulses, despite the inertia of the active medium. The new method makes it possible to form in Yb-doped fibre lasers a stable regular sequence of nanosecond and, potentially, subnanosecond pulses of coherent radiation even with relatively slow ($\tau > 1$ μs) and shallow (∼50 %) modulation of the pump radiation power. The method is based on introducing a small (less than 0.1 %) mismatch between the period of sinusoidal pump power modulation and the group delay of the laser pulse during its roundtrip in the fibre resonator. Under certain conditions, this leads to an effective shortening of the circulating pulse in the active laser fibre due to gain discrimination at the trailing edge of the pulse. Because of the nonrigorous synchronisation of the pump modulation with the intrinsic (not imposed) roundtrip time of the laser pulse, the method was called quasi-synchronous pump modulation [11]. The method provides high stability of the lasing parameters and a low noise level, comparable to those achieved using classical methods of active mode locking; moreover, it possesses advantages of implementation simplicity, high reliability, and energy efficiency due to the absence of any intracavity modulators.

In this work, we investigate for the first time additional capabilities of quasi-synchronous pumping in Yb-doped fibre lasers. In particular, the possibility to generate stationarily a regular sequence of high-energy pulse clusters with a controlled number of nanosecond subpulses in the cluster is demonstrated. In addition, the possibility of using the quasi-synchronous pumping in lasers with double-clad fibres and high-power multimode pump sources is investigated for the first time. It is shown that in such lasers it is possible to increase the energy of nanosecond laser pulses generated using quasi-synchronous pumping significantly (at least up to 430 nJ).

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Received 26 October 2021
Kvantovaya Elektronika **51** (12) 1061 – 1067 (2021)
Translated by V.L. Derbov

2. Experiment

2.1. Polarisation-maintaining laser pumped into the active fibre core

We investigated two configurations of Yb fibre lasers with ring resonators, consisting entirely of polarisation-maintaining (PM) fibres and PM fibre-optic elements.

In the first of the considered laser configurations, a ring resonator was used (Fig. 1), similar to that used in Ref. [11] to study the mechanism of the formation of short single pulses due to quasi-synchronous modulation of the pump power. This scheme ensures counterpropagation of pump and lasing waves, preventing pump radiation unabsorbed in the active fibre from entering the output coupler.

This laser used a core-pumped Yb-doped active polarisation-maintaining fibre 0.55 m long (LIEKKI Yb700-6/125-PM). A 30% fused coupler provided the output of radiation from the resonator. In the laser resonator, a narrow-band (2 nm) spectral filter with the centre of the passband near 1064 nm was also used. The filter was installed to block parasitic radiation [amplified spontaneous emission and stimulated Raman scattering (SRS)]. In addition, the filter provided selection and stabilisation of the generation wavelength. The resonator was lengthened by inserting a passive single-mode polarisation-maintaining fibre with a length of ~0.9 km (Fujikura, 980 nm band PANDA fibre). The resulting optical length of the resonator corresponded to a fundamental pulse repetition rate of ~230.5 kHz. A radiation source with a wavelength of 980 nm based on laser diodes with a single-mode fibre output was used for pumping. The maximum pump power supplied to the laser was ~1.05 W. A fibre spectral multiplexer was used to inject the pump radiation into the resonator. The pump power was modulated by changing the current of the pump source laser diodes. For this purpose, a signal from an RF arbitrary waveform generator was fed to the modulation input of the current drivers.

In accordance with the concept of quasi-synchronous pumping [11], pulsed lasing is triggered by sinusoidal modulation of the pump power with a frequency slightly (by about 0.1%) higher than the fundamental pulse repetition rate (~230.5 kHz), which is determined by the optical length of the resonator. To obtain pulses of the shortest duration, a smooth decrease in the initially overrated modulation frequency and its approach to the fundamental frequency is required. In the experiment, the frequency step was 5 Hz with a time interval of 0.5 s. With such a tuning of the modulation frequency, a smooth transition occurs from a shallow sinusoidal modulation of the cw lasing power to the formation of discrete nanosecond pulses (Fig. 2a). The corresponding evolution of the optical emission spectrum is shown in Fig. 2b, and Fig. 3 shows oscillograms of the pump and lasing powers for the selected values of the modulation frequency. It should be noted that in this study, at the modulation depth set to be ~83%, the instantaneous value of the pump power always remained above the lasing threshold (more than 90 mW).

As follows from the measurement results, the minimum duration of a single pulse (~205 ns) is achieved at the modulation frequency F_1 = 230.685 kHz. In this case, the contrast in the generated sequence of laser pulses was ~99%, and their energy (taking into account the contrast) was ~130 nJ. As shown in Ref. [11], the possibility of further decreasing the duration of a single pulse is limited primarily by the excessive nonlinear incursion of the pulse optical phase caused by an increase in the pulse peak power with a decrease in its duration. Therefore, a further gradual decrease in the modulation frequency to values below 230.685 kHz leads to switching the laser to a multi-pulse lasing regime, as evidenced by the frequency-time distributions of the lasing intensity in Fig. 2a and the oscillograms in Fig. 3.

Investigation of the frequency domain of multipulse generation showed that the lasing regime is deterministic (reproducible) rather than stochastic and allows controlling the number of subpulses that make up a regular pulse cluster.

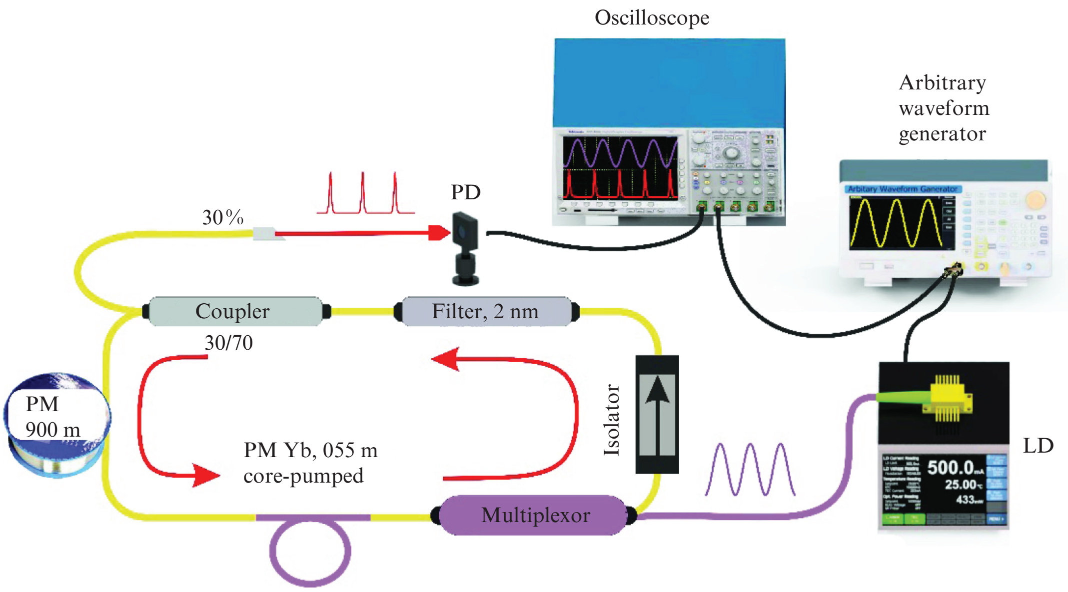

Figure 1. (Colour online) Schematic of an Yb fibre laser pumped into the core of a single-mode active fibre: (LD) pump laser diode with a single-mode fibre output; (PM Yb) single-mode polarisation-maintaining ytterbium-doped fibre; (PM 900 m) spool of passive polarisation-maintaining fibre.

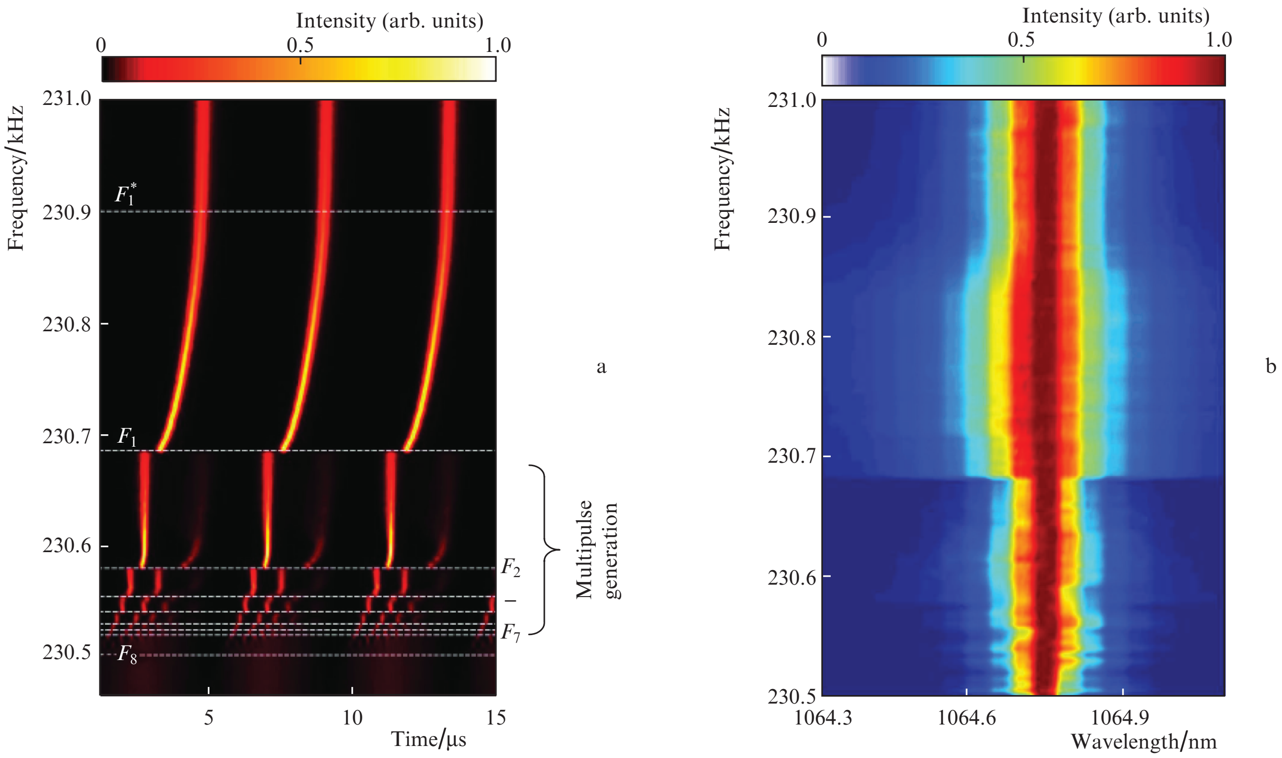

Figure 2. (Colour online) (a) Frequency and time distributions of the lasing intensity upon tuning (decreasing) the pump modulation frequency near the fundamental pulse repetition rate and (b) the corresponding evolution of the spectral distribution of the lasing intensity; F_1, F_1^*, F_2,..., F_8 are selected modulation frequencies, for which Fig. 3 shows oscillograms of the resulting laser pulses.

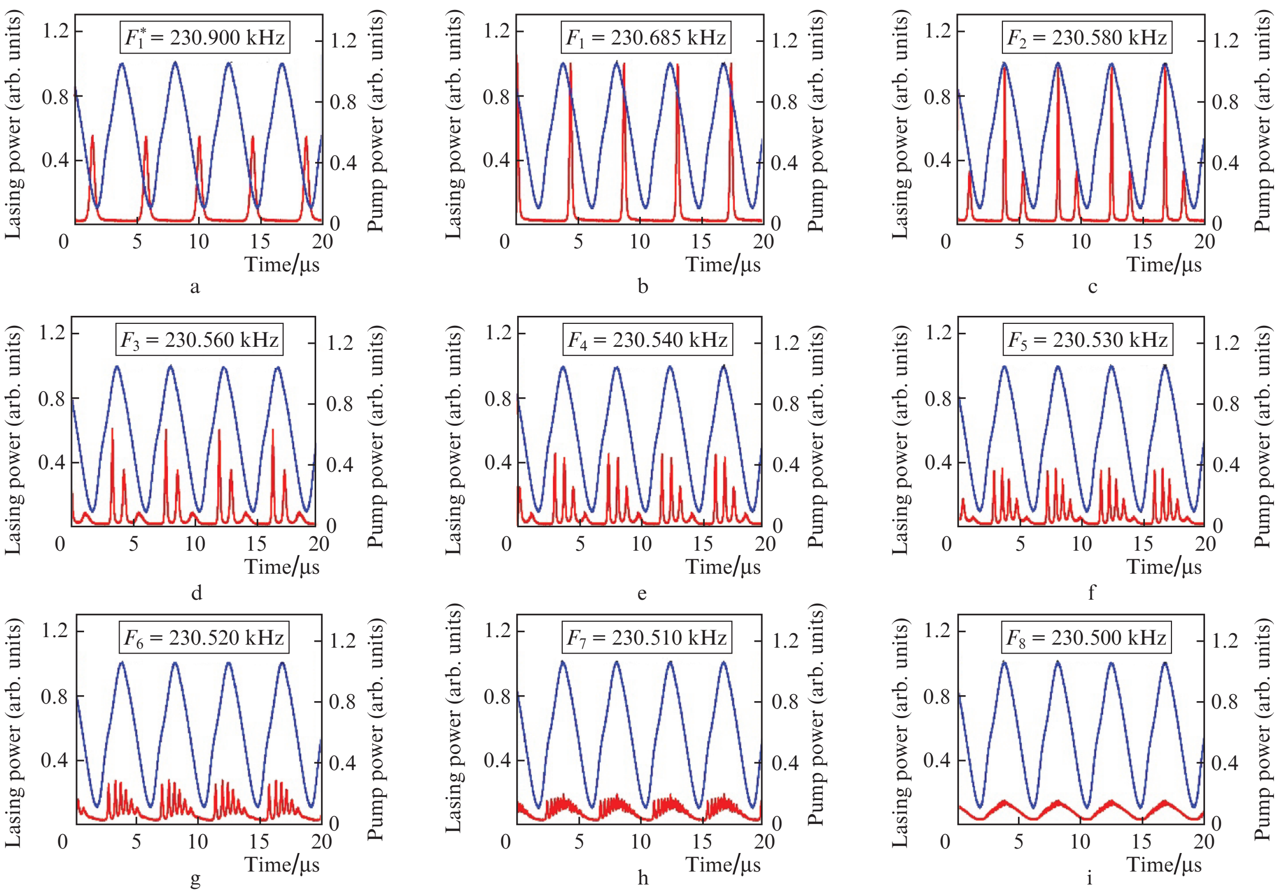

Figure 3. (Colour online) Oscillograms of the pump power (blue curves) and lasing power (red curves) for selected values of the modulation frequency.

Figures 3c–3h show oscillograms of pulse clusters with the number of subpulses from 2 to 7, which are obtained by tuning the modulation frequency from F_2 = 230.580 kHz to F_7 = 230.510 kHz. The cluster is formed within the time interval corresponding to the pump power modulation period. With an increase in the number of subpulses in the cluster, their duration decreases down to ~100 ns (in the case of seven subpulses). The total energy of subpulses in the cluster is invariably equal to 130 nJ. The indicated multi-pulse regimes are stable as well as the single-pulse oscillation regime, and are maintained by the laser under laboratory conditions throughout a working day. The resulting generation of pulse clusters corresponds to the stationary lasing regimes predicted by us in the numerical model [11] for the case of an infinitely small positive detuning of the modulation frequency from the fundamental pulse repetition rate (230.5 kHz), specified by the optical length of the resonator.

Figure 4 shows the experimental dependence of the laser pulse duration on the pump power modulation frequency obtained in this work near the fundamental pulse repetition rate (with decreasing modulation frequency). With a further decrease in the modulation frequency to the fundamental frequency and below, the laser switches to the cw regime with a shallow sinusoidal modulation of the radiation power (see Fig. 3i).

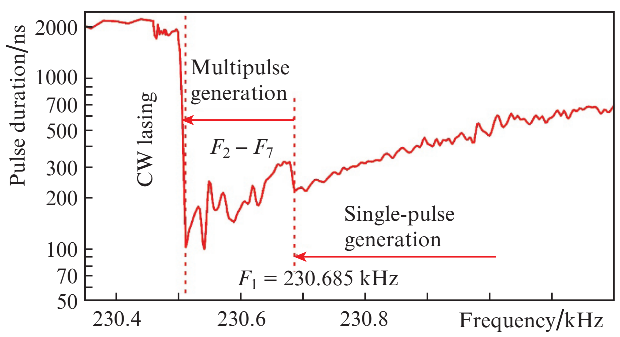

Figure 4. (Colour online) Dependence of the laser pulse duration on the pump power modulation frequency near the fundamental pulse repetition rate.

The demonstrated possibility of generating regular high-energy pulse clusters with an electronically controlled number of nanosecond subpulses can be used in lidar technologies [12], as well as in the study of complex effects of nonlinear interaction of radiation with matter [13].

2.2. Polarisation-maintaining laser with high-power multimode pumping through the cladding of active fibre

To investigate the feasibility of scaling the energy of laser pulses formed using the method of quasi-synchronous modulation of the pump power, we tested a modified laser configuration with an ytterbium-doped double-clad fibre (double-clad Yb fibre) and a high-power multimode pump source.

The second of the considered laser configurations had a resonator similar to the first one (Fig. 5), the difference was mainly in the use of a highly doped double-clad Yb fibre (LIEKKI Yb1200-6/125DC-PM). The length of the active fibre was 5 m. In the modified configuration, instead of a spectral multiplexer, a special fibre combiner was used to inject multimode pump radiation from a high-power (10 W) source into the inner cladding of the active fibre. A laser diode with a multimode fibre output of radiation at a wavelength of 980 nm was used as a pump source. The rest of the laser elements did not change. At the expense of a slight increase in the optical length of the resonator (due to the use of a longer active fibre), the fundamental pulse repetition rate (determined by the resonator length) decreased and amounted to ~228.1 kHz. In contrast to the initial configuration, in the system under consideration, the pump laser diode current driver allowed only pulsed modulation of the pump power

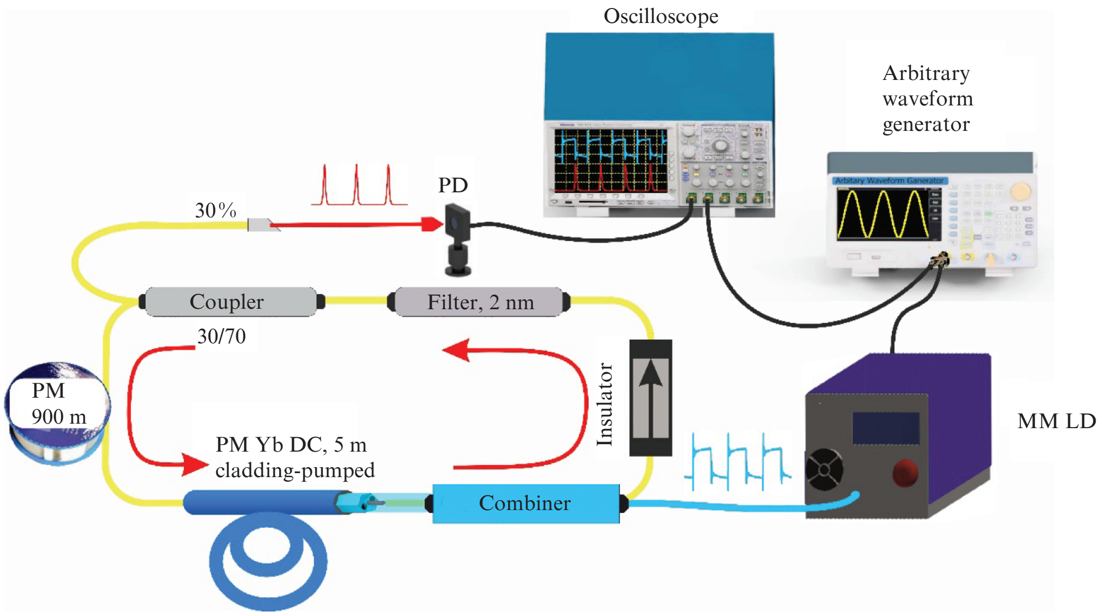

Figure 5. (Colour online) Schematic of the high-energy Yb fibre polarisation-maintaining laser pumped through the inner cladding of the active fibre: (MM LD) high-power pump laser diode with multimode fibre output; (PM Yb DC) polarisation-maintaining double-clad Yb fibre; (PM 900 m) spool of passive polarisation-maintaining fibre.

with a duty cycle of approximately 50%. Because of the limited bandwidth of the current driver, the optical pump signal had a distorted h-shape (instead of a rectangular shape of the driving electric pulses).

Pulsed lasing was initiated by applying a clock signal with a frequency slightly (by 0.1%) higher than the fundamental pulse repetition rate (~228.1 kHz) to the pump laser diode current driver.

Despite noticeable distortions in the shape of the optical pump signal (an overshoot at the leading edge and a tail at the pulse trailing edge), with a smooth decrease in the initially overrated modulation frequency and its approach to the fundamental frequency, a regular sequence of short single bell-shaped laser pulses was formed. In the experiment, the frequency step was 10 Hz with a time interval of 0.5 s. The frequency-time distributions of the lasing intensity in Fig. 6a demonstrate a smooth transition from shallow quasi-sinusoidal modulation of cw radiation to the formation of discrete nanosecond pulses. The corresponding evolution of the optical radiation spectrum is shown in Fig. 6b. Figure 7 shows oscillograms of the pump and lasing powers for the selected values of the modulation frequency.

As follows from the measurement results, the minimum duration of a single pulse (~330 ns) is achieved at the modulation frequency F_1 = 228.680 kHz. In this case, the contrast in the generated sequence of laser pulses exceeded 98%, and their energy (considering the contrast) was ~430 nJ. The noise characteristics were close to those of typical mode-locked fibre lasers: the signal-to-noise ratio in the RF spectrum near the fundamental pulse repetition frequency exceeded 46 dB and the amplitude fluctuations from pulse to pulse were less than 2% (Fig. 8).

With a further gradual decrease in the modulation frequency to values below 228.680 kHz, the laser switches to the oscillation regime of so-called pulse patterns, the shape of which correlates with the h-shape of the pump pulses, as evidenced by the frequency-time distributions of the lasing power in Fig. 6a and the oscillograms in Fig. 7. The total energy of the generated pulse patterns is invariably ~430 nJ. The generation of specific pulse patterns instead of the generation of pulse clusters, which took place in the initial laser configuration, can be explained by a significant difference in the shape of the pump power modulation. The resulting pulse patterns are as stable as the single-pulse generation regime, and are maintained by the laser under laboratory conditions throughout the entire working day. With a further decrease in the modulation frequency to the fundamental frequency and below, the laser switches to the cw oscillation regime with a shallow quasi-sinusoidal modulation of the radiation power (Fig. 7f). Figure 9 shows the obtained experimental dependence of the laser pulse duration on the pump power modulation frequency near the fundamental pulse repetition rate.

The experimentally demonstrated possibility of increasing the energy of laser pulses obtained by the method of quasi-synchronous pump modulation to 430 nJ and more opens up wide potentialities for the implementation of this method in high-power and high-energy fibre laser systems, including systems intended for laser processing of materials

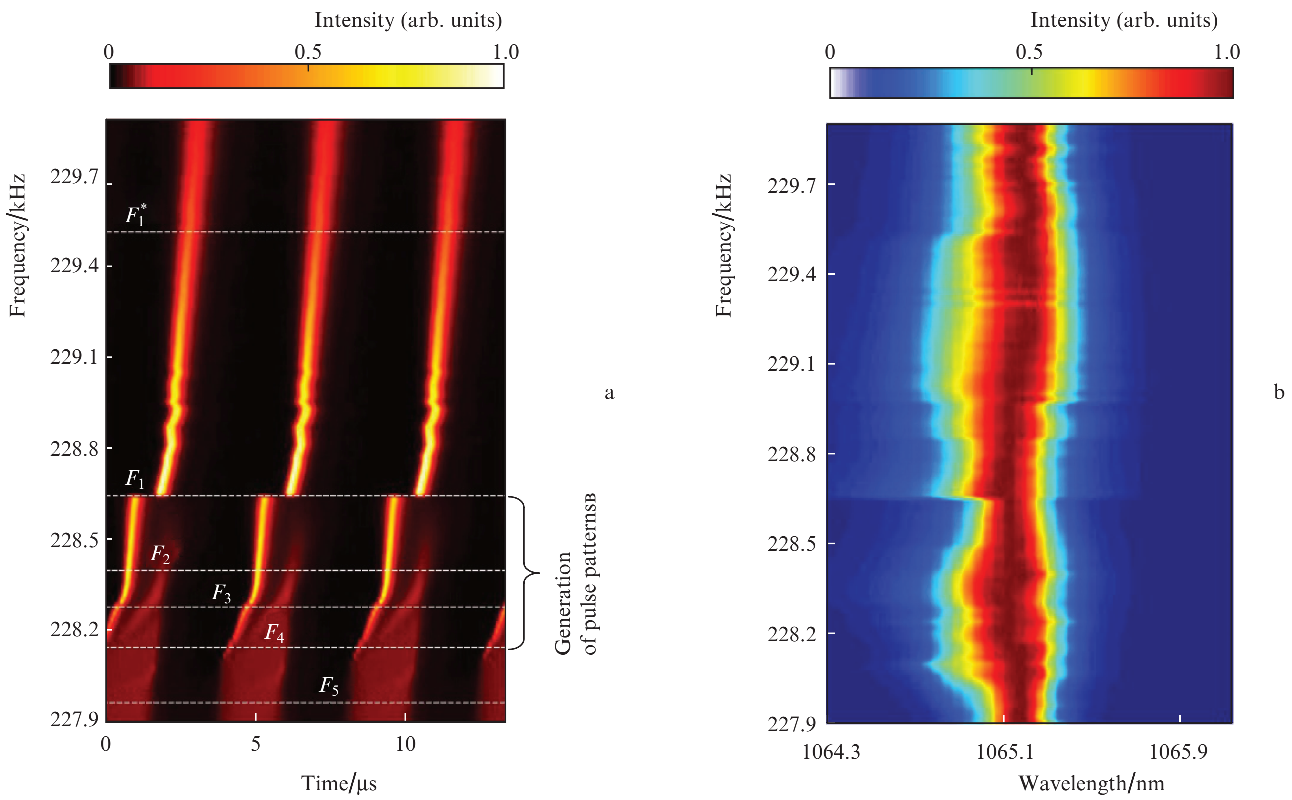

Figure 6. (Colour online) (a) Time and frequency distributions of the lasing intensity upon tuning (lowering) the modulation frequency of the pump power near the fundamental pulse repetition rate and (b) the corresponding evolution of the spectral distribution of the lasing intensity; F_1, F_1^*, F_2,…, F_5 are selected modulation frequencies, for which Fig. 7 shows oscillograms of the resulting laser pulses.

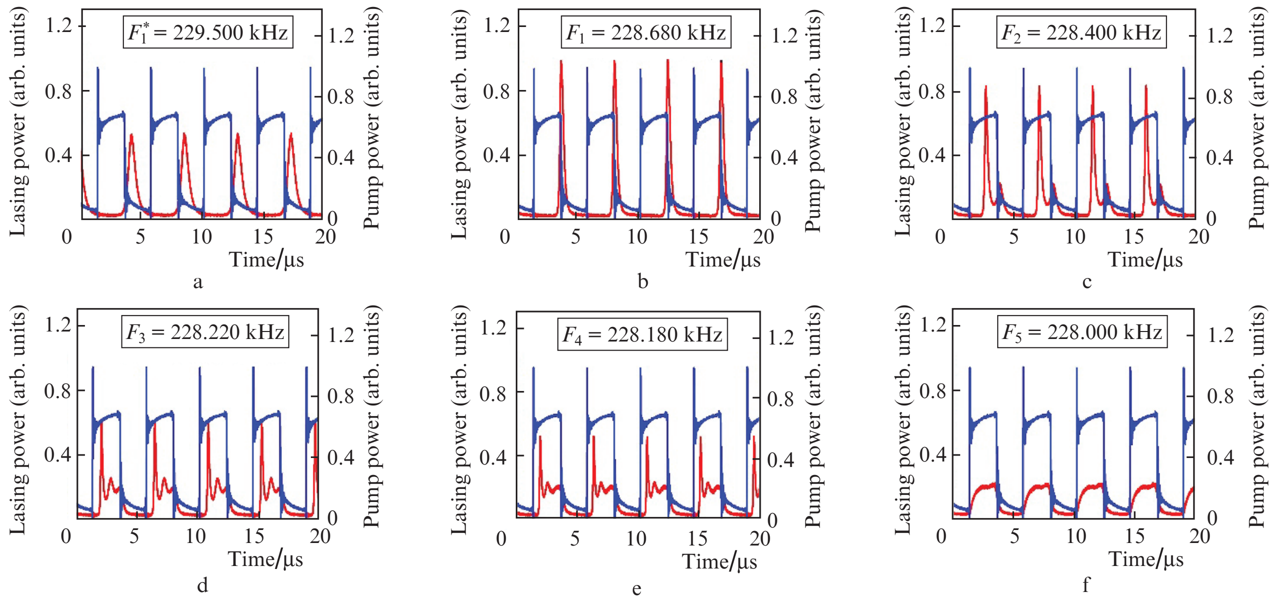

Figure 7. (Colour online) Oscillograms of the pump (blue curves) and lasing (red curves) powers for selected values of the modulation frequency.

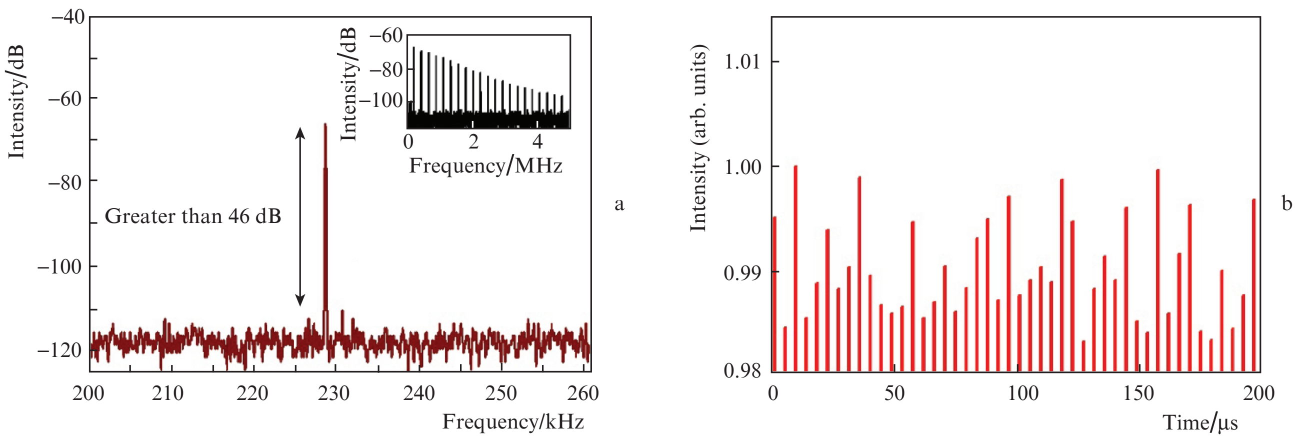

Figure 8. (Colour online) (a) Radio-frequency spectrum of a regular sequence of single nanosecond laser pulses and (b) oscillogram of their amplitude fluctuations.

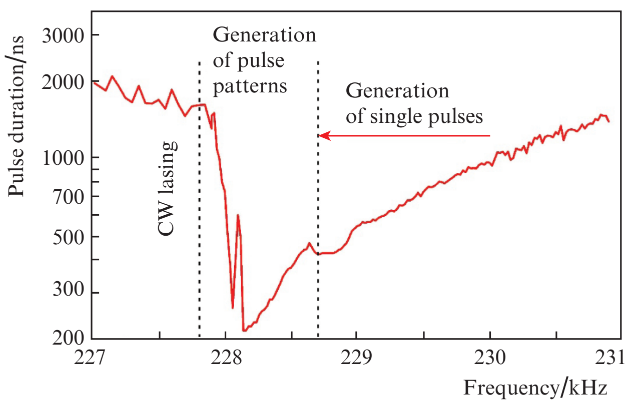

Figure 9. (Colour online) Dependence of the laser pulse duration on the pump power modulation frequency near the fundamental pulse repetition rate.

[14]. It should be noted, however, that the potential for a further increase in pulse energy (accompanied by an increase in peak power) might be limited by factors such as the accumulation of excessive nonlinear phase incursion by the pulse and reaching the SRS threshold, as shown in [11]. Nevertheless, in the presented nanosecond laser systems, the peak radiation power at the entrance to the 900-m passive fibre section of the resonator was significantly lower than the calculated critical power ($P_{cr} \approx 8$ W) corresponding to the SRS threshold [15]. In addition, in both laser configurations, a narrow-band spectral filter was installed in front of the output coupler, which prevents the possible contribution of the Stokes components of the SRS into the output radiation.

At the same time, of interest may also be the potential possibility of simultaneous generation of pulses at the fundamental and Stokes wavelengths, which, probably, can be realised with the appropriate modification of the laser resonator by analogy with [16].

3. Conclusions

The paper presents additional possibilities of quasi-synchronous pumping in Yb fibre lasers. In particular, generation of a regular sequence of high-energy pulse clusters with a controlled number of nanosecond subpulses in a cluster has been obtained for the first time. The transition to such a regime is possible under conditions of an extremely small (less than 0.1%) positive detuning of the modulation frequency from the fundamental pulse repetition rate specified by the optical length of the resonator, when the critical peak power is reached. Approaching the specified frequency provides a sequential increase in the number of coupled subpulses in the generated regular pulse clusters. In this case, the total energy of subpulses in the cluster remains unchanged and reaches 130 nJ at the output of a simple experimental configuration of a laser pumped into the core of a polarisation-maintaining ytterbium-doped fibre.

The applicability of the quasi-synchronous pumping method is experimentally demonstrated in high-power and high-energy fibre laser systems using active double-clad fibres and high-power multimode pump sources. Proceeding to such laser architecture (high-power pumping through the cladding of the active fibre) has made it possible to obtain nanosecond pulses with an energy of 430 nJ by means of quasi-synchronous pumping, leaving the potential for a further increase in the pulse energy.

The results obtained offer new prospects for the widespread use of the quasi-synchronous pumping method in conventional fibre lasers based on stimulated emission for solving various scientific and applied problems related, in particular, to lidar measurements, materials processing, and the study of complex nonlinear effects arising from the interaction of laser radiation with various optical materials and metamaterials. The investigated lasers join the ranks of new types of fibre laser oscillators with active electronic control of pulsed lasing parameters [17–19]. Due to the ultra-long polarisation-maintaining fibre resonator, they are also of interest as a base for studying the prospects for developing an active telecommunication link with the possibility of cryptographic protection at the physical layer.

Acknowledgements. This work was partially supported by the Russian Foundation for Basic Research and the Novosibirsk Region (Project Nos 20-42-543007 and 19-42-540013), as well as the Ministry of Science and Higher Education of the Russian Federation (Project FSUN-2020-0007).

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