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New regime of single-pulse lasing in fibre lasers with mode locking by nonlinear polarisation evolution

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Abstract. **A new lasing regime has been obtained experimentally and as a result of numerical simulation of fibre lasers with mode locking by nonlinear polarisation evolution. This regime differs radically from the previously known regimes of stable single-pulse lasing and generation of wave packets with quasi-stochastic filling. The spectral and temporal features of the pulses generated in the new regime, as well as the possibilities of pulse compression, have been investigated. Simple criteria are formulated, which make it possible to identify rapidly the new lasing regime in experiment.**

Keywords: *fibre laser, ultrashort pulses, nonlinear polarisation evolution.*

1. Introduction

Fibre lasers with all-normal group velocity dispersion of the cavity medium and mode locking due to the nonlinear polarisation evolution (NPE) are relatively simple and high-efficiency devices for generating ultrashort pulses. For this reason, they have been actively investigated in the last years. As compared with mode-locked lasers based on saturable absorbers, the lasers of this type are characterised by a simple and reliable design and the absence of semiconductor and other elements whose characteristics may change irreversibly under light. Their advantage in comparison with anomalous-dispersion soliton lasers is the possibility of generating higher energy (by an order of magnitude or more) pulses without their decay [1 – 4]. The pulse energy in lasers with all-normal dispersion intracavity medium can be increased even more by elongating the cavity. Since the pulse repetition rate in a passively mode-locked laser is inversely proportional to its length, the pulse energy increases linearly with an increase in the cavity length at a fixed average lasing power. This approach was demonstrated most effectively in [5], where an elongation of the fibre laser cavity to 3.8 km yielded pulses with energy of 3.9 μJ, a record value for mode-locked master fibre generators.

The experiments of the last years on NPE lasers with all-normal dispersion, having both short and long cavities, demonstrated a variety of lasing regimes, which can be separated into two types: mode-locking regime, in which several radiation pulses are present simultaneously in the laser cavity in each instant [6, 7], and a regime in which a laser generates a single pulse during cavity round trip. We will refer to the second case as a single-pulse regime specifically in the sense of generation of a single pulse (which can be a train and consist of several subpulses) during cavity round trip. In this paper, we report the results of studying specifically the new regime of single-pulse generation of NPE lasers with all-normal dispersion. Note that lasers of other types, including lasers mode-locked by saturable absorbers (SESAM, carbon nanotubes) and NPE lasers with total positive dispersion, may possess different sets of lasing regimes [8, 9].

As was shown previously, in the case of single-pulse lasing at a fixed pump power, lasers of this type can generate pulses with different energy and duration at different tunings of polarisation elements [10]. Moreover, the generated pulses may not only differ in energy and duration but also have radical distinctions. In this context, the problem of classifying the implemented lasing regimes arises, which is important for optimal laser tuning. Previously, the single-pulse regime of noise-like (or quasi-stochastic) lasing, along with generation of single bell-shaped pulses, was reported in [10 – 13]. Wang et al. [14] noted four experimentally obtained lasing regimes; however, no general basis was proposed to classify the experimental observations. A more general separation of lasing regimes into stable and quasi-stochastic ones was proposed in [10].

In this study we prove (based on experimental results and numerical simulation) the existence of a new lasing regime, which is intermediate between the stable single-pulse lasing and quasi-stochastic generation of wave packets. Some characteristic features of the new regime are revealed, such as the shape of the spectrum and the intensity autocorrelation function (ACF). The compressibility of the laser pulses generated in the new regime is also investigated.

2. Laser scheme and numerical model

The experiment was performed on the same ring scheme of an ytterbium-doped fibre cavity as in our earlier study (see [10] and Fig. 1). The active medium was a 7-m-long segment of an ytterbium-doped fibre with a core diameter of 7 μm. The fibre was pumped by a 1.5-W diode laser at a wavelength of 980 nm. The radiation polarisation was controlled using two fibre polarisation controllers PC1 and PC2.

To increase the cavity length and pulse energy, we used a segment of standard fibre SMF-28, and the total cavity length was 11.2 m (the cavity round-trip time τ = 54 ns). All optical fibres we used had a normal dispersion of group velocities at lasing wavelengths. The average lasing power was limited by

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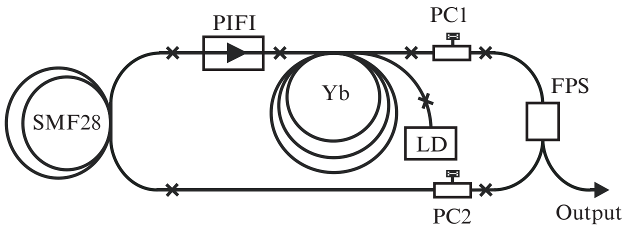

Figure 1. Schematic of the experimental setup: (PC1, PC2) polarisation controllers, (PIFI) polarisation-independent fibre insulator, (FPS) fibre polarisation splitter, (LD) pump laser diode, and (Yb) active ytterbium-doped fibre.

the operating range of fibre polarisation divider and did not exceed 150 mW.

To gain a deeper insight into the experimental results, we performed numerical simulation of this laser using a standard approach, based on the system of generalised nonlinear Schrödinger equations [15]:

$$\begin{aligned}\frac{\partial A_x}{\partial z} &= \mathrm{i}\gamma\left\{|A_x|^2 A_x + \frac{2}{3}|A_y|^2 A_x + \frac{1}{3}A_y^2 A_x^*\right\}\\ &\quad + \frac{g_0/2}{1+E/(P_{\mathrm{sat}}\tau)}A_x - \frac{\mathrm{i}}{2}\beta_2\frac{\partial^2 A_x}{\partial t^2},\\ \frac{\partial A_y}{\partial z} &= \mathrm{i}\gamma\left\{|A_y|^2 A_y + \frac{2}{3}|A_x|^2 A_y + \frac{1}{3}A_x^2 A_y^*\right\}\\ &\quad + \frac{g_0/2}{1+E/(P_{\mathrm{sat}}\tau)}A_y - \frac{\mathrm{i}}{2}\beta_2\frac{\partial^2 A_y}{\partial t^2},\end{aligned} \tag{1}$$

where A_x and A_y are the orthogonal components of the field envelope; z is the longitudinal coordinate; t is time; $\gamma = 4.7\times10^{-5}$ cm^{-1} W^{-1} is a nonlinear coefficient; g_0 is the small-signal gain; $\beta_2 = 23$ ps^2 km^{-1} is the dispersion coefficient; P_{sat} is the saturation power for the active fibre; and τ is the cavity round-trip time. The simulation was performed disregarding the higher order dispersion effects and the linear birefringence of the fibre. The amplifier parameters were estimated from the experimental data to be $g_0 = 540$ dB km^{-1} and $P_{\mathrm{sat}} = 52$ mW. To improve the convergence of the solution to the limit cycle of equations, we supplemented the numerical model with a spectral filter having a bandwidth of 30 nm, a value exceeding significantly the typical spectral widths of generated pulses. The spectral selection in the experiment is due to the gain profile of the active fibre, as well as the efficient operation of the optical fibre and fibre polarisation splitter as a Lyot filter [16]. The effect of polarisation controllers was taken into account in the model via unitary matrices (see, for example, [10, 17]).

3. Results and discussion

The results of experiments and numerical simulation showed that NPE lasers with all-normal dispersion allow for many lasing regimes; they can be switched during laser operation by changing the tunings of intracavity polarisation elements. The pulses generated in different regimes differ in energy and duration, shape of envelope, and spectral width. Another important distinction of lasing regimes is their short-term stability (from pulse to pulse). This parameter affects significantly the pulse compression, which is necessary for a number of applications of lasers with a high normal cavity dispersion. In addition, the short-term stability determines the shape of the spectrum of a pulse sequence (an equidistant line comb or a smooth continuous spectrum), which can be important, for example, for metrological applications of these lasers and supercontinuum generators on their basis.

Previously we reported observation of lasing regimes with a high short-term stability (with fluctuations of parameters from pulse to pulse on the order of $10^{-6}-10^{-4}$) and generation of wave packets with highly fluctuating (noise-like) filling [10]. A distinctive feature of the stable lasing regime is the bell-shaped ACF and a sharp-edge spectrum; the spectral power density rapidly decreases even on the logarithmic scale [10]. On the contrary, the lasing spectrum in the stochastic regime is bell-shaped and the ACF of wave packets with noise-like filling has a characteristic ‘double’ shape (a femtosecond peak against the picosecond background), which is due to the presence of two time scales in the pulse: the time coherence scale for wave packets and the scale of the subpulses filling this spectrum [10].

Our detailed study showed that there is an intermediate regime (which was not observed previously) between the two aforementioned lasing regimes. The lasing spectra observed in the new regime are characterised by sharp edges and smooth falloff of the spectral power at the base. The ACF of the pulses has a characteristic double structure; however, the peak height is much smaller than the background. Thus, both the spectrum and the ACF in the new regime are intermediate between the spectra and ACF of the stable lasing regime and the generation of wave packets with stochastic filling (see Fig. 2). Note also that the shape of the ACF background can be different at different tunings of polarisation elements. In particular, the simulation gave ACFs of triangular shape [14]; however, these ACFs always contained a femtosecond peak at the centre, which indicated either noise-like lasing or the intermediate regime.

In view of the good qualitative agreement between the results of numerical simulation and the experimental data on the spectra and ACF (see Fig. 2), numerical simulation can be used for a more detailed study of the properties of the new lasing regime. In particular, Fig. 3 shows the time dependences of the pulse intensity and instantaneous frequency detuning $\Delta\nu = -(\mathrm{d}\varphi/\mathrm{d}t)/(2\pi)$, which were obtained in the numerical simulation. Experimental study of the pulse phase is a technically difficult problem, especially with allowance for the stochastic character of the lasing under study, whereas these dependences can be obtained relatively simply by numerical simulation.

One can see from Fig. 3 that the pulse generated in the new (intermediate) regime is noise-like: it contains irregular intensity oscillations with respect to some bell-shaped envelope. Note that the amplitude of these oscillations is below the average value; thus, the function $I(t)$ does not decrease to zero at the pulse centre. The time dependence of the instantaneous frequency detuning $\Delta\nu(t)$ also contains high-frequency fluctuations, which limit significantly the degree of pulse compression. According to the numerical simulation, the maximum degree of time compression in the diffraction-grating compressor in our case is $k_{\max} = 4.75$ (note for comparison that the limit compression value would be two orders of magnitude larger in the absence of frequency fluctuations: $T_0/T_{\mathrm{peak}}^{\min} \approx 300 - 400$, depending on the pulse shape). The

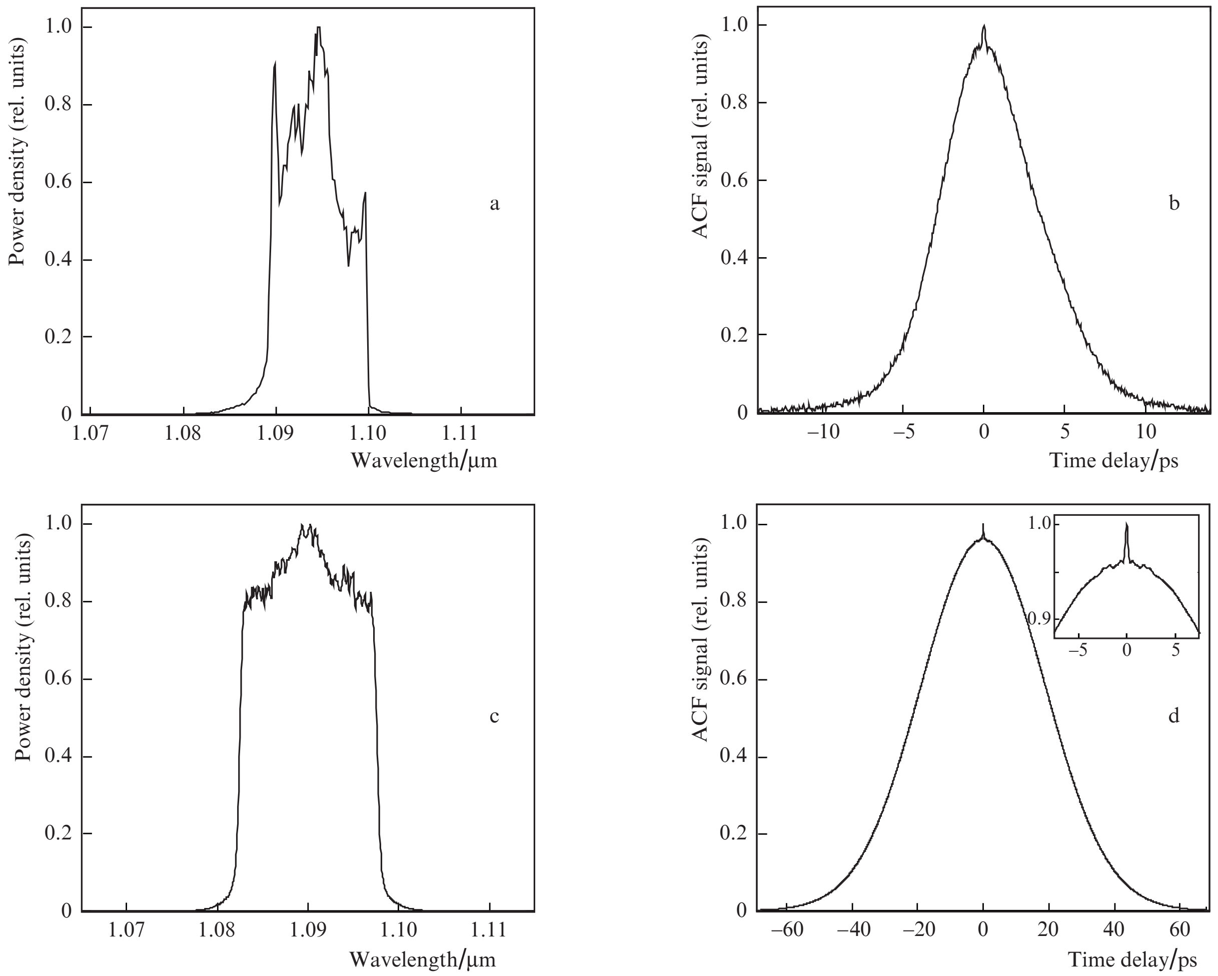

Figure 2. (a, b) Experimental and (c, d) model (a, c) spectral power densities and (b, d) ACFs in the new lasing regime.

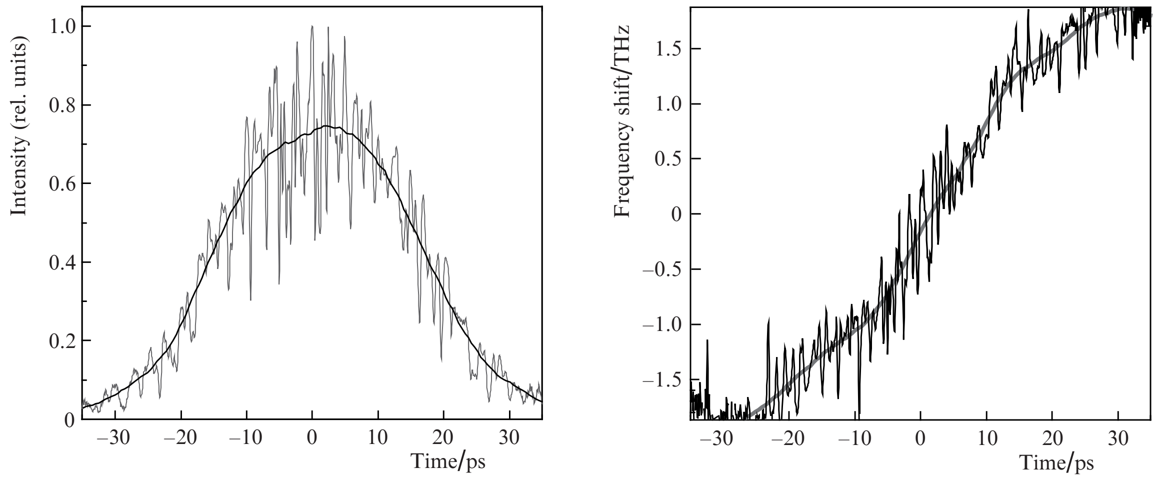

Figure 3. Time dependences of the intensity and instantaneous frequency shift Δν for the new lasing regime (result of numerical simulation).

result obtained is in good agreement with the experimental data: the compression of pulses with ACF in the form of background with a small peak gives a decrease in the pulse duration by a factor of 3 – 5; hence, the parameters of compressed pulses remain to be very far from transform-limited.

4. Conclusions

We showed for the first time, both experimentally and using numerical simulation, the existence of a new lasing regme in fibre lasers with all-normal dispersion and passive mode locking due to nonlinear polarisation evolution. The properties of the new regime condition its intermediate position between the previously known stable single-pulse regime and the regime of quasi-stochastic generation of wave packets. The characteristic features of the new regime, due to which it can easily be identified in experiment, is the sharp-edge spectrum and a smooth falloff of spectral power at the base, as well as the double (pico- and femtosecond) form of the ACF, with a small height of femtosecond peak. The pulse intensity contains high-frequency fluctuations; however, it does not decrease to zero in the pulse, in contrast to the quasi-stochastic lasing. The pulse phase contains also small oscillations, which lead to significant fluctuations of instantaneous frequency, thus limiting significantly the degree of compression of these pulses in optical compressors.

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