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Numerical study of passively mode-locked soliton fiber laser

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Abstract

We present the results of numerical modelling of the Figure-8 laser. By slowly changing of pump power we have observed development of the laser radiation and a process of transformation of noise-like temporal structure into clean solitons.

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Passively mode-locked soliton fiber lasers (PSLs) based on the Nonlinear Amplifying Loop Mirror (the figure-8 laser) have recently become of considerable interest owing to their ability to produce ultra-short pulses from a simple cavity configuration and also due to the many physical effects involved in the laser action and affecting the laser output [1-3]. This laser demonstrates many interesting features such as the existence of soliton and non-soliton components in the laser output and energy quantization [4], resulting in a dependence of the number circulating pulses on laser pump power and fixed parameters for the generated pulses.

In this paper we present the results of a numerical study of the Figure 8 laser. Using a simple model, based on the Nonlinear Schrödinger equation we demonstrate that in order to reach qualitative agreement between the numerical and experimental results one has to consider at least a two-pulse regime of laser operation. Our computer results permit us to evaluate parameters of the system such as the NALM switching efficiency and the number of round trips to reach self-start the extraction of which from experimental data is a difficult problem.

In our computer simulations we have been looking at the laser characteristics as a function of pump power by evaluating the laser behaviour as the pump power is gradually changed by small steps starting from an initial value below the second threshold. The numerical procedure was as follows: at a certain level the pump power is held fixed for several round trips (usually 20-50) until the system comes to a steady state regime. The pump power is then increased by 2-5% and fixed again and the new steady state obtained. During the first 1000 round trips the pump power is increased and in the last 1000 round trips the pump power is decreased.

Our computer simulations show that the model describes the development of the self-start mode-locked regime from low-level spontaneous noise. Depending upon the amplifier saturation intensity the model gives a one- or two-pulse regime of laser output. The numerical study shows that the single pulse regime of a PSL can bring only information about the ability of the system to self-start the mode-locked regime; studying this regime it is impossible to make any conclusions about the parameters of the individual pulses. The regime with two pulses within the cavity dramatically changes the results of the computer simulations relative to the case of a single pulse and gives reasonably good agreement with the experimental results.

Figure 1 (a-c) shows the dependencies of the laser output on the pump power in the two-pulse regime - full energy (a), pulse duration (b) and switching efficiency (c) (i.e. transmission of the NALM). Based on the numerical results we can identify six regions of the laser output: cw operation (1), cw operation within the hysteresis region (2), transient region of self-start (3), the steady-state regime of self-start mode-locked operation above second threshold (4), a region of mode-locked operation below second threshold (5) and a region of cessation of passive mode-locking (6).

For the first 100 round trips the noise-like intracavity optical field has no well-defined peak fluctuation (even the time position of the peak intensity undergoes random fluctuations) despite an increase in the average intensity. A two fold pump power increase leads to a 10 times growth in peak intensity. The time duration of the peak fluctuations remains almost unchanged. The initial value of the switching efficiency is determined by the phase bias between the counterpropagating waves. During first few round trips switching efficiency is low (less then 20%) and decreases with increasing pump power. This reduction of switching efficiency with pump power causes significant growth of the effective gain.

The onset of self-start mode-locking is easily noted by the abrupt change in all dependencies in Fig. 1. A few percent increase in pump power causes a sharp change in the laser output parameters: a well-resolved maximum of intensity fluctuation arises and does not dissapear over subsequent round trips. The peak intensity of this fluctuation and the full energy of the laser field increase by several orders of magnitude depending upon the parameters of the system. The duration of the intensity fluctuation begins to decrease due to the nonlinearity and a soliton-like pulse appears. The switching efficiency increases by 3-4 times and together with saturation of amplification results in a decrease of the effective gain. Note that passive mode-locking takes place at N =340 and starts with a certain delay with respect to the consequent pump power change: it takes around 20 round trips to form a distinguishable fluctuation peak. Note, that in our model a further increase of pump power after the self-start point results in a stable two-soliton mode of operation (a hump in region 4). Above the hump the peak intensity does not change significantly despite the growth in the average output power and results in a reduction in switching efficiency to approximately 50%. The reason for this is the significant contribution of the nonsoliton component to the laser output.

The pulse duration of the steady-state soliton is constant over a wide region of pump power being essentially defined by the length of the nonlinear loop. Decreasing the pump power (last 1000 round trips) leads to a one-pulse mode that can not be reached directly from noise level. When the system turns into the regime of single pulse operation the laser output is stable over a wide range of pump powers. After each change of the pump power small oscillations appear but are quickly suppressed after 1-2 round trips. All parameters have extreme values in this region that correspond to the point of maximum switching efficiency when the differential nonlinear phase shift is exactly equal to π.

In summary, using a simple numerical model we have analysed the behavior of a passively mode-locked fibre laser. As a particular example of a PSL we have chosen the Figure 8 laser which possesses all features characteristic of soliton lasers. The results of the numerical study are in qualitative agreement with experimental data. The proposed analysis can be used for the description of other types of passively mode-locked fibre laser.

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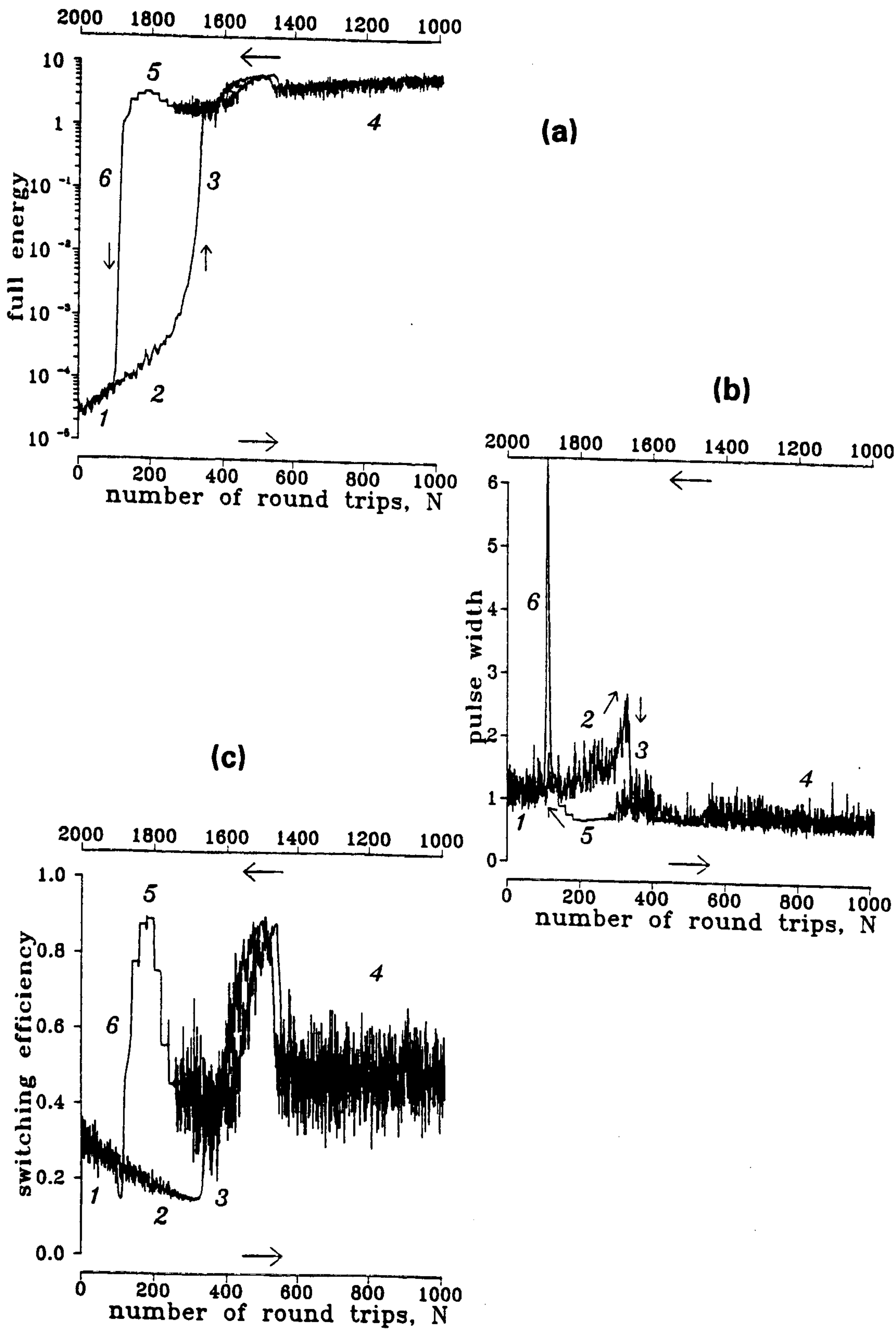

Fig.1 Output characteristics of the PSL in the two-pulse regime

(a) full energy

(b) pulse duration

(c) switching efficiency.