Experimental study of the stochastic nature of the pulsation self-starting process in passive mode locking

Boris Vodonos, Alexander Bekker, Vladimir Smulakovsky, Ariel Gordon, Omri Gat, Naum K. Berger, and Baruch Fischer

Department of Electrical Engineering, Technion, Haifa 32000, Israel

Received April 7, 2005; revised manuscript received June 15, 2005; accepted June 16, 2005

We present an experimental study of the probabilistic nature of pulsation self-starting in passively mode-locked lasers. It is a Poissonian process that results from a noise-activated switching barrier. The switching rate from cw operation to pulsation when the laser pump level is turned on has an exponential dependence that is inversely proportional to the square of the laser power. © 2005 Optical Society of America

OCIS codes: 140.4050, 140.3430.

Self-starting pulse operation of passively mode-locked lasers occurs when a certain threshold value of the intracavity power is reached. The origin of this power threshold was discussed previously.[1–3] The arguments were that some sort of randomness (such as reflections in the cavity), decoherence, and noise in the laser cavity oppose the nonlinearity of the saturable absorber that causes mode locking. The threshold condition for self-starting was obtained as a requirement that the intracavity power times the nonlinearity coefficient (characterizing the saturable absorber) be greater than a typical scale associated with the suggested disturbance.

A recent study of mode locking introduced a statistical mechanics many-body (many-mode) approach and gave a fundamental description of the pulse formation that is inherent in passively mode-locked lasers.[4–8] The onset of pulses was shown to be a first-order power- and noise-dependent phase transition between a disordered quasi-continuous-wave regime and ordered mode-locked pulsed operation. The statistical mechanics theory predicts that for low intracavity power or high noise power the stable state, in a thermodynamic sense, of a passively mode locked laser is a continuous-wave (cw) state. The stabilization mechanism is entropic and results from the many-mode nature of the quasi-cw state. When the intracavity power increases or noise decreases, the mode-locked state becomes thermodynamically stable. Analysis shows, however, that the cw state remains metastable for any intracavity power,[6] as it is a local minimum of the thermodynamic potential. Therefore, even for high power and low noise, mode locking will not self-start until a transition across the noise- and light-power-dependent barrier to the globally stable mode-locked state is activated by an appropriate fluctuation provided by noise itself (or, as it is known among laser operators, by a “morning starter-kick” of the laser table top). Thus self-starting is an essentially stochastic process, which determines the lifetime of the metastable cw state. A probabilistic study of the self-starting in pulse lasers is of much interest.

Self-starting dynamics was addressed in a recent theoretical study.[9] It is based on an analysis of the coarse-grained version of the master equation with additive noise.[7] The stochastic equation governing the dynamics of pulse power x derived in Ref. 9 may be written as

$$\frac{\mathrm{d}x}{\mathrm{d}t} = Nf(x) + g(x)\,\eta(t), \tag{1}$$

where N is the number of active modes in the initial cw state and η is a white-noise process whose covariance T is the noise power injection rate, which plays the role of effective temperature. When T is small enough or the intracavity power P is strong enough, then f is bistable, with a local minimum at $x=0$, corresponding to the metastable cw state. Escape from the cw state is therefore the noise-activated process in which a rare fluctuation of noise term $g(x)\eta(t)$ in Eq. (1) drives x across the barrier. The activation barrier is high because of the large factor N that multiplies the deterministic term in Eq. (1); this is the basic reason that self-starting is so difficult.

The dynamics of one-dimensional activation, such as given by Eq. (1), is well understood,[10] and it is obtainable as a simple limit of the escape problem first studied by Kramers within the context of chemical reactions.[11] The most important predictions that result from application of the Kramers theory to the self-starting problem are that the distribution of self-starting events is Poissonian and that the logarithm of the mean lifetime of the metastable cw state is approximately proportional to the ratio of the barrier height to the activation strength, a result also known as the Arrhenius formula. Recently, polarization switching of single-mode vertical-cavity surface-emitting lasers was identified as a Kramers hopping problem,[12] and the stochastic effects observed in such lasers have been subjects of theoretical and experimental studies.[13]

As explained above, the expected long-time behavior of the lifetime probability distribution is Poissonian, with a characteristic exponential tail

$$Pr_{\mathrm{cw}}(t) = \exp(-t/\tau_{\mathrm{cw}}), \qquad (2)$$

where τ_{cw} is the characteristic cw lifetime. This universal form of lifetime probability distribution in noise-activated escape systems is basically a consequence of the great length of the metastable state's lifetime compared with dynamical time scales, during which the system may be said to perform many unsuccessful attempts before activation is successful. The first major result of this Letter is an experimental demonstration of the Poisson lifetime distribution, which proves the noise-activated nature of self-starting.

An interesting aspect of our theory of self-starting of mode locking is the dual role of the noise that determines two ingredients of the process[6,9]: The height of the entropic barrier, which traps the cw state, is proportional to T^2, as well as the strength of the fluctuations that eventually drive the laser out of the metastable cw state across the barrier to the mode-locked state whose variance is proportional to T. The activation barrier is also inversely proportional to P^2.

In our experiments, only intracavity power P is changed, while other parameters, including the noise level, are kept fixed. Under these conditions, according to the Arrhenius formula,

$$\log \tau_{\mathrm{cw}} \sim 1/P^2. \qquad (3)$$

The experimental verification of this prediction is the second major result of this Letter, confirming the entropic nature of the activation barrier.

Our experimental system is schematically shown in Fig. 1. The laser under study was an erbium-doped fiber ring laser passively mode locked by the nonlinear polarization rotation technique.[14,15] By insertion of a polarizer into the laser cavity, the effect of nonlinear rotation of polarization is translated into power-dependent losses. Thus a fast saturable-absorber action is effectively implemented, and a passive mode-locking operation can be established. The gain in the laser was provided by a 1.2 m long erbium-doped fiber. The total cavity length was ~20 m. The passive mode-locking power threshold was achieved at a laser pump current of ~70 mA. The laser-produced subpicosecond pulses at an ~10 MHz repetition rate.

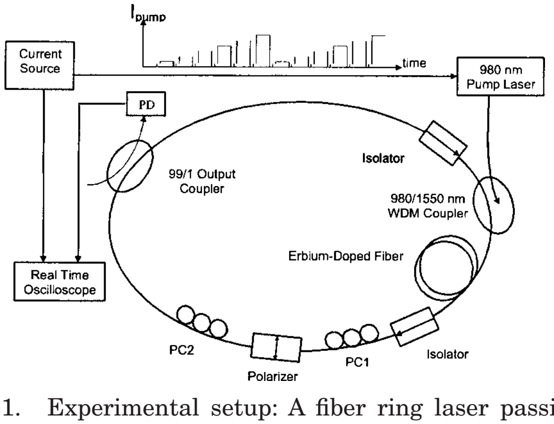

Fig. 1. Experimental setup: A fiber ring laser passively mode locked by nonlinear polarization rotation was switched on and off by modulating the pump current. The self-starting dynamics was measured by photodetector PD and a real-time oscilloscope.[8] WDM, wavelength-division multiplexer; PC1, PC2, polarization controllers.

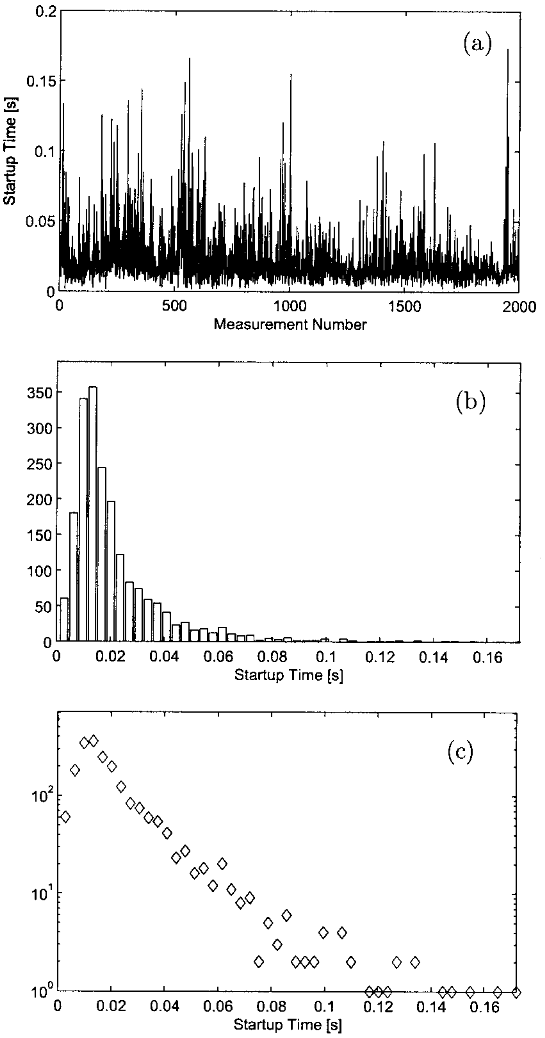

Fig. 2. Example of a measured distribution of the startup times for a pumping current of 88 mA presented (a) as a time recording of the experimental data and in the form of a histogram (2000 measured points distributed among 50 bins) on (b) linear and (c) logarithmic scales.

For a quantitative study of the self-starting dynamics we used modulated pumping to switch the mode-locked laser operation on and off with different current levels. A three-level current signal with a typical cycle duration of 1 s was used to drive the pump laser diode. A short (one tenth of a cycle) interval of zero current switched the laser operation off; an intermediate current level, whose duration was also one tenth of a cycle, was chosen to bring the laser just below the self-starting power threshold, and a high current was applied for the pulse operation of the laser. We used envelope detection of the laser output to measure directly with a real-time oscilloscope the startup times that are given by the delay between turning the pump laser to the high current level and starting the pulsation. In six succesive cycles we applied six different high current levels, and, afterward, this process was repeated periodically as shown in Fig. 1. On switching from the cw regime to

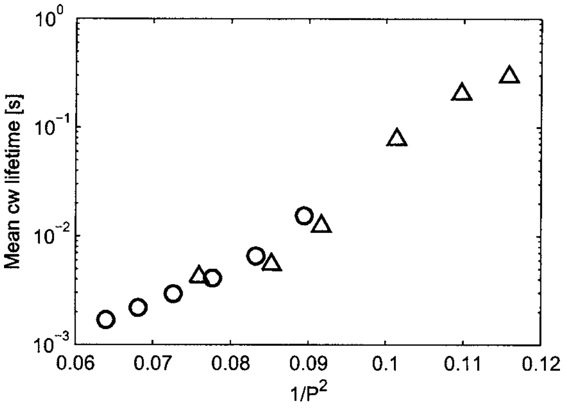

Fig. 3. Dependence of mean cw lifetime on intracavity power P. The results are for two sets of measurements (circles and triangles). The estimated mean cw lifetime is shown versus $1/P^2$ on a logarithmic scale.

mode locking, the laser undergoes complicated transient dynamics (exhibiting self-Q switching) before ordered pulsed operation is established.[16]

An example of the measured startup times and their statistical distribution for a pumping current of 88 mA is shown in Fig. 2, where the measured startup times are plotted. As expected, the startup time has a lower bound imposed by a dynamic light buildup time scale in the cavity (inversely dependent on the intracavity power). Then comes the stochastic transition process with the decay time of cw to pulsation. The characteristic exponentially decreasing tail of this time is seen in the measured distribution.

We have also conducted an experimental study of the mean lifetime dependence on intracavity power P. We note that a comprehensive investigation of the theoretical prediction for the exponential behavior and longer startup times (operation near the self-starting threshold) should be examined, requiring long sustained measurements of the self-starting statistics and bringing forward the issue of long-term laser stability. Besides its dependence on intracavity power and noise, the mean lifetime is also dependent on saturable-absorption properties.[4] However, since the saturable-absorber action is implemented in our fiber laser by a distributed effect of nonlinear polarization rotation, fluctuations in environmental conditions, such as vibrations and slow temperature drift, cause fluctuations in the strength of the saturable absorption. With continuous pumping the mode-locked operation may remain stable for many hours because the laser can slightly self-tune the pulse parameters. However, repeated switching of the laser on and off, especially near the self-starting threshold, causes the long-term stability to deteriorate. The stability issue was dealt with by improving the thermal and acoustic isolation of our fiber laser system and making the measurements in the specific order described above. We measured the startup times for a number of different pumping currents for different values of the intracavity power (P) and then repeated that sequence. Then essentially the same operation conditions were preserved for all sets of measurement points in the short term.

Measurements of the mean lifetime are shown in Fig. 3 as a function of the intracavity power for two different sets of measurements with overlapping ranges of pumping currents (both measured at nearly identical operation conditions), demonstrating the predicted exponential dependence.

In conclusion, we have presented an experimental study of the stochastic dynamics of the self-starting of passive mode locking, demonstrating that it is a Poisson process with a characteristic lifetime that depends exponentially on the inverse of the squared intracavity power.

This research was supported by the Israel Science Foundation of the Israel Academy of Science. B. Vodonos's e-mail address is barac@tx.technion.ac.il; B. Fischer's is fischer@ee.technion.ac.il.

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