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Starting dynamics of dissipative-soliton fiber laser

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Abstract

We study the starting dynamics of an all-normal-dispersion Yb-doped fiber laser experimentally and compare them to an existing stochastic model of starting from quantum noise. The laser reaches mode locking 10 to 100 times faster than a soliton laser with similar parameters. According to the model, the fast starting can be attributed to the large pulse energy in the normal-dispersion laser. We also report direct observations of starting from relaxation oscillations and discuss that process in light of the theory.

The field of ultrafast science and technology depends on the availability of sources of ultrafast pulses, and this has motivated extensive studies of pulse evolution in mode-locked lasers. The phase locking of a large number of longitudinal cavity modes is a fascinating process, and the self-starting is an important practical attribute of a mode-locked laser. Quite a few studies of the starting dynamics of mode-locked lasers have been reported [1–16]. To date, all work on starting dynamics has addressed lasers with anomalous cavity group-velocity dispersion (GVD) and solitonlike pulse shaping. These studies have considered solid-state lasers and Er-doped fiber lasers.

A number of models have been proposed to explain the observed threshold power for the mode locking, and these tend to focus on the competition between phase locking and decoherence processes [2–7,9,10,13]. Recently, Vordonos *et al.* and Gordon *et al.* developed a stochastic theory of the onset of mode locking, in which starting is viewed as a noise-induced escape over an entropic barrier, and mode locking constitutes a thermodynamic phase transition [15,16]. This model indicates that quantum noise initiates the pulsation, and the free-running cavity modes are coupled together by the saturable-absorber nonlinearity. The GVD, which is crucial to the steady mode-locked state, is not a factor in the starting dynamics.

Normal-dispersion femtosecond lasers, in which pulses are dissipative solitons, have demonstrated major performance advantages [17,18]. Here we report a study of the starting dynamics of an all-normal-dispersion (ANDi) fiber laser. The stochastic theory accounts for the starting dynamics under some conditions, although the starting times are ~10 times faster than in soliton lasers, owing to higher pulse energies. In addition, we directly observe the influence of relaxation oscillations on the starting, which can speed up the starting process by another order of magnitude.

The starting dynamics of an Yb-doped soliton fiber laser were measured as a control experiment. The laser is described in [19], and the fiber lengths and grating pair were chosen for a net cavity GVD of -0.18 ps^2 . Nonlinear polarization evolution acts as the saturable absorber. The repetition rate is 46 MHz, and the intracavity pulse energy is 0.6 nJ. With these parameters, the laser operates in the soliton regime [Fig. 1(a)]. The pulse is transform limited, with 700 fs duration and 0.4 nJ output energy. A mechanical chopper is placed inside the cavity. An InGaAs detector is used to monitor the pulse energy, and a GaAsP photodiode, which only detects $1 \mu\text{m}$ light through two-photon absorption, monitors the peak intensity.

Typical measured traces are shown in Fig. 1(b). We define the zero of time as when the cavity mode is first completely unblocked by the chopper wheel. Aliasing produces structure in the pulse energy trace, but it does not interfere with the analysis, because we are interested only in the position when the trace rises above the noise floor. The starting time is defined as when the laser reaches the mode-locked state, as indicated by a stable two-photon current level. Fluctuations in the peak power are observed before the onset of mode locking. The distribution of time intervals between peak fluctuations can help unveil the origin of fluctuations. We recorded thousands of pulse energy and peak intensity traces and analyzed their statistical properties.

The results are similar to those of prior measurements of soliton lasers [1–16]. The start times exhibit an exponential distribution [Fig. 1(c)], which implies that the fluctuations are dominated by quantum noise [16]. The peak fluctuation time intervals also obey the exponential distribution [Fig. 1(d)], which indicates that the peak fluctuation birth rate is constant in time, another signature of quantum noise. The average start time is 100 ms, close to the results in [16].

The normal-dispersion regime is accessed by removing the grating pair from the laser and adding a filter; the setup is otherwise unchanged. The resulting GVD is 0.08 ps^2 , and the repetition rate is 52 MHz. The spectrum [Fig. 2(a)] exhibits the steep sides and cat-ear structure of a dissipative-soliton formation. The chirped output pulse is 10 ps in duration, and it can be dechirped to 200 fs, near the transform limit. The pulse energy ranges from 3 to 5 nJ, depending on the pump power. Example traces of the pulse energy and peak power are shown in Fig. 2(b). Peak intensity fluctuations occur before the mode-locked state is reached, as in the soliton case. In the ANDi laser, short-lived pulsations occur after each peak fluctuation but fail to reach the steady mode-locked state.

Although the pulse evolution in the ANDi laser is very different from soliton evolution, the distributions of the start times and fluctuation intervals [Figs. 2(c) and 2(d)] are exponential and again indicate the dominant role of quantum noise. However, the start times range from $140 \mu\text{s}$ to 14 ms, which is 1 order of magnitude shorter than the start times in the soliton laser. The start time varies rapidly with the intracavity pulse energy [Fig. 2(e)], as predicted by the stochastic model [16]. The fluctuation interval ranges from $70 \mu\text{s}$ to 2 ms and exhibits an analogous dependence on pulse energy. Higher cavity energy produces a higher peak fluctuation birth rate and in turn a shorter starting time.

Starting dynamics in soliton and dissipative-soliton lasers are similar (although with distinct time scales) because dispersion and the refractive nonlinearity have little impact on the initial pulse formation. When mode locking is starting, fluctuations occur on the scale of mode beating: hundreds of picoseconds to nanoseconds. Thus only the saturable-absorber nonlinearity couples free-running cavity modes. These conditions are consistent with the assumptions of the stochastic model [16], which account well for the experimental observations.

Sources of noise other than quantum noise can contribute to the initial fluctuations. In the course of these experiments, we configured the ANDi laser to operate with increased output coupling. The spectrum [Fig. 3(a)] is essentially unchanged, and the pulse duration is unchanged. Under these conditions, the pulse energy and peak power undergo regular and periodic variations [Fig. 3(b)], in contrast to the random fluctuations presented above. The peaks have instrument-limited duration of 1 μ s. The peak interval distribution [Fig. 3(c)] is localized around 70 μ s, and its width decreases with increasing pulse energy. The distributions of peak positions and starting times overlap substantially [Fig. 3(d)], so starting is clearly correlated with the strong pulsation.

The parameters of the Yb fiber lasers studied here imply that relaxation oscillations should occur with periods of 40 to 80 μ s and damping times of 10 to 150 ms. The period of observed pulsations is plotted versus the pulse energy in Fig. 3(e) along with the values calculated from a standard model of relaxation oscillations [20]. The good agreement supports the assignment to relaxation oscillations.

Remarkably, we are unable to find any previous literature report of the role of relaxation oscillations in the starting of mode locking. The relaxation oscillation facilitates the starting; the laser reaches the steady mode-locked states within 200 μ s, or less than three periods [Figs. 3(c) and 3(d)]. The starting time is around 100 μ s with 3 nJ energy, and it decreases to around 50 μ s at 5 nJ energy, much faster than when the fluctuations are random. The relaxation oscillations are more likely to occur with higher intracavity energy; no relaxation oscillations are observed when the energy is below 1 nJ. Beyond that, we are unable to state specific conditions or a procedure that is certain to produce the relaxation oscillations. Mode-locked states that appear to be identical from the standard diagnostics (pulse energy, spectrum, and autocorrelation) may or may not exhibit relaxation oscillations in the starting process. We conjecture that initial conditions of the atom and the field parameters may determine why one noise source dominates a starting event. Perhaps accurate measurements of the noise spectrum [21] will be able to shed light on this. The influence of relaxation oscillations (or more generally, of gain and loss dynamics) on steady-state mode-locking stability is well known and is typically observed as sidebands in the radio frequency spectrum. Even when the starting dynamics exhibit the relaxation oscillations, as in Fig. 3(b), we fail to observe them in the steady-state spectrum, which means that they are attenuated by at least 70 dB relative to the mode-locked peak.

In all the cases presented here, the overall structure of the starting time distribution is exponential, which is a feature of the first-order escape process [16]. It can be viewed as a trial-and-success process. Whenever there are intensity fluctuations of any origin, the system tries to reach the steady mode-locked state until it succeeds. Thus, the starting time distribution in all cases is exponential, but the fluctuation source can add some features to the distribution, such as in Fig. 3(d), when relaxation oscillation dominates. The stochastic model does not accurately predict the dependence of starting time on pulse energy [Fig. 3(f)], presumably because it does not consider deterministic sources of fluctuations.

In conclusion, we have studied the starting of mode locking in an ANDi fiber laser. A stochastic theory of the mode-locking transition accounts well for the experiments when the starting is from quantum noise. The laser starts 10–100 times faster than soliton lasers, owing to higher pulse energies. This rapid starting may be valuable to some applications of these lasers. We also observe starting from relaxation oscillations, apparently for the first time. Starting is closely correlated to relaxation oscillations when they occur, and the starting time decreases significantly compared to starting from quantum noise. Future work will address why quantum noise or relaxation oscillations control the starting, along with any connections to the steady-state noise spectrum.

Acknowledgments

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Fig. 1.

(Color online) Results from soliton laser: (a) spectrum, (b) pulse energy and two-photon absorption traces, (c) start time histogram and exponential fit, (d) peak fluctuation interval histogram and exponential fit. The peak intervals are the time intervals between peaks P1, P2, and P3 in Fig. 1(b). Peak positions are defined as where the peaks start.

Fig. 2.

(Color online) Results from ANDi laser: (a) spectrum, (b) pulse energy and two-photon absorption traces, (c) start time histogram and exponential fit, (d) peak interval histogram and exponential fit, (e) intracavity energy versus start time, fitted by the model in [16], and (f) intracavity energy versus peak interval and exponential fit.

Fig. 3.

(Color online) Results that show relaxation oscillations. (a) spectrum, (b) pulse energy and two-photon absorption traces, (c) peak interval histogram and Gaussian fit, (d) start time and peak position histograms, and best-fit exponentially-decaying sinusoid, (e) intracavity energy versus oscillation period. Symbols are measured and line is model of [20], with parameters $K \sim 10^{-3}$, $N \sim 5 \times 10^8$, $\gamma_c \times 10$ to 50 ns, $\gamma_2 \sim 2.3$ ms for each cavity mode, $r \sim 2$ to 20, [20], and (f) intracavity energy versus start time and best-fit model in [16].