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Fiber Lasers Mode-Locked Due to Nonlinear Polarization Evolution: Golden Mean of Cavity Length

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Abstract—Recent results on the pulsed generation in high-energy fiber lasers that are passively mode-locked owing to the nonlinear polarization evolution are generalized for the first time. The first analysis of the cavity length that is optimized with respect to practical applications is presented. The analysis is based on the concordant experimental results and the results of numerical simulation.

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INTRODUCTION

Over almost two decades [1, 2], the nonlinear polarization evolution (NPE) is used for passive mode locking in fiber and bulk/fiber lasers that generate short optical pulses. A distinctive feature of such lasers is a relatively large number of parameters (tunable intracavity polarization elements) that can be varied in real time in the course of lasing. Owing to this feature, the NPE lasers are interesting for physical experiments, since they allow various regimes of lasing. For example, the laser that exhibits the stable mode-locked cw lasing (generation of a train of identical pulses) or the *Q*-switched lasing was reported in [3, 4]. Note that the switching of the regimes results from the tuning of the polarization controllers. Variations in the parameters of the polarization controllers allows the suppression of sidebands in the laser spectrum, so that almost bandwidth-limited pulses with a duration of only 132 fs can be generated in the NPE laser [5]. The NPE lasers also exhibit the stable multipulse lasing, which involves the intracavity propagation of several pulses (up to 23 pulses in [6]). The multipulse lasing was supplemented with significant variations in the spectral shape with variations in the pump power in [7]. Under certain conditions, the multipulse lasing leads to the condensation of pulses in the cavity, so that single pulses (dissipative solitons) that are continuously added to the condensed state resemble water droplets that fall to sea [8]. Another interesting regime of the NPE lasers involves the multiwave lasing. The solitons were simultaneously generated at two wavelengths and the interaction of such solitons was studied in [9]. The multiwave lasing with the generation of radiation whose spectrum represents a frequency comb was reported in [10]. The generation at several wavelengths was demonstrated for the NPE lasers based on active fibers doped with ytterbium [11–14] and erbium [5, 15, 16]. The application of the intracavity spectral filters and the ultrabroadband loop mirrors based on fiber circulators allows wide-range wavelength tuning of ultrashort pulses [17].

Easy assemblage and a relatively high output power (high pulse energy) are important advantages of the passively mode-locked NPE lasers with regard to practical applications. Relatively high pulse energies are reached due to the absence of intracavity saturable semiconductor absorbers and other elements with low damage thresholds and the application of the all-normal-dispersion intracavity fiber. Thus, the power limitations that are inherent in soliton lasers are eliminated. Note the recent analysis of the methods for an increase in the energy of ultrashort pulses due to an increase in the length of the laser cavity. The lasing in the cavities with lengths of several kilometers at pulse energies of up to 4 μJ was recently demonstrated in [14, 16, 18, 19]. One of the first applications of the ultralong lasers was the generation of the high-energy supercontinuum [19–21].

However, our experimental results from [14, 18–21] show that an increase in the cavity length leads to complications in the tuning of the mode locking needed for the generation of a train of single pulses and to a decrease in the stability of the mode-locked laser. In addition, the conventional methods that are employed in short lasers do not allow the compensation for the gigantic phase modulation that emerges in the ultralong cavity of the all-positive-dispersion laser.

In this regard, we consider a practically important problem that involves a search for the golden mean of the cavity length at which the passively mode-locked NPE laser is sufficiently stable and allows the generation of high-energy single pulses that can be compressed using conventional techniques (e.g., with the aid of a pair of diffraction gratings or prisms).

The topicality of the problem is related to the fact that the experimental works on the mode-locked NPE lasers were performed using either stable short cavities with lengths of several meters or ultralong cavities with lengths of greater than 1 km that allow the generation

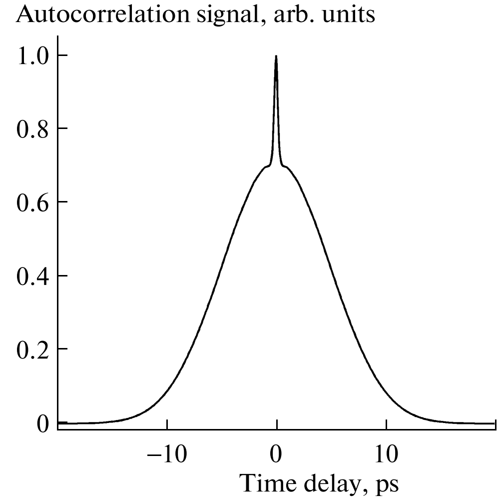

Fig. 1. The typical ACF of the laser pulse intensity for the stochastic lasing (result of the numerical simulation from [22]).

of high-energy pulses at ultralow repetition rates [12, 13]. In this work, we analyze and generalize the existing data on lasers in which the mode locking results from the NPE effect and consider new works with the medium cavity lengths that range from several tens to several hundreds of meters.

MODE LOCKING IN SHORT CAVITIES

The passive mode locking in the NPE lasers with cavity lengths of several meters (for simplicity, we call them short lasers) was reported in [1–6, 12, 22]. The mode locking in short NPE lasers is well studied. The lasing in various regimes was theoretically [23] and experimentally [6] demonstrated. In this work, we concentrate on the stability of lasing and, hence, classify the regimes in short lasers as the stable mode locking and stochastic regimes. In the first case, the laser generates a train of single bell-shaped pulses whose parameters (e.g., shape of envelope, duration, and energy) exhibit a relatively high pulse-to-pulse stability. As distinct from the first regime, the second regime involves the generation of wave packets with complicated shapes that consist of multiple subpulses. The numerical simulation from [22] shows that the number, duration, and energy of such subpulses exhibit significant packet-to-packet variations. Moreover, such variations can lead to fluctuations of energy and duration of wave packets in general.

A typical feature of the stochastic regime is the dual shape of the autocorrelation function (ACF) of the pulse intensity: a narrow (femtosecond or subpicosecond) peak is observed against a broad (picosecond) pedestal (Fig. 1). Such a specific shape of the ACF is related to the presence of two time scales of the coherence time: the duration of the wave packets in general (the scale that corresponds to the pedestal) and the duration of the stochastic subpulses contained in the wave packets (the scale that provides the narrow peak). Note that the substructure of pulses is absent in the stable regime of the single-pulse lasing and the bell-shaped ACF is measured in experiments [18, 22].

In accordance with the results from our previous work [22], the transition of the NPE laser with the normal dispersion of the intracavity fiber from one regime to another is accompanied with variations in the ACF and the shape of spectrum. In the case of the stable pulsed lasing, the spectrum exhibits steep edges, and, in the stochastic regime, we obtain the bell-shaped spectrum (Fig. 2 and [22]). This feature is more convenient for the experimental identification of the regime.

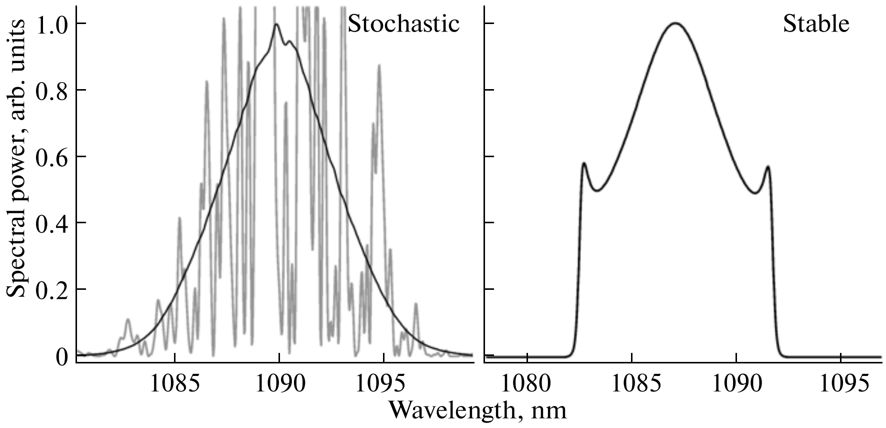

Fig. 2. Laser radiation spectra for (left-hand panel) stochastic and (right-hand panel) stable single-pulse lasing. For the stochastic regime, the gray line shows the spectrum of a wave packet and the black line shows the result of averaging over the ensemble of laser pulses (result of the numerical simulation from [22]).

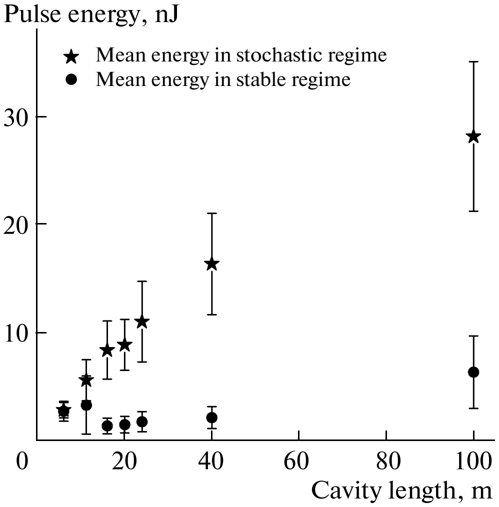

Fig. 3. Numerically simulated plot of the pulse energy vs. cavity length. The spreads of values correspond to the intervals of the pulse energies obtained at various tuning parameters of the polarization controllers in the numerical simulation.

The stability of mode locking must be considered at different time scales. First, we consider the time interval between pulses (the round-trip time of the cavity, which is about 1 ns for the short lasers) and the laboratory time scale, which corresponds to the continuous work of the laser (one or several hours). The stability of the laser pulses on the time scale of the interpulse interval is used to identify the above regimes (stable and stochastic). In each regime, we consider the stability on the longer time scale and analyze the drift of parameters in time and the spontaneous suppression of the regime.

The experiments show that the short lasers exhibit the stable mode locking on both time scales and provide the pulse-to-pulse stability over several hours. The tuning of the polarization elements leads to the stochastic regime of lasing, which is even more stable than the single-pulse mode locking over long time intervals in spite of the pulse-to-pulse fluctuations. This circumstance means that the parameters of laser pulses exhibit fluctuations at the pulse repetition rate when the drift of the mean parameters of such fluctuations is absent in the laser. Evidently, the stability is an important advantage of the short lasers with regard to practical applications. The disadvantage of the short cavity is a relatively low pulse energy, which is insufficient for several applications.

MODE LOCKING IN ULTRALONG CAVITIES

An obvious method for an increase in the pulse energy involves the extracavity amplification. However, such an approach necessitates significant complications of the laser setup related to the application of an additional amplification stage with the optical pumping unit. Note also that a pulse stretcher must be used to avoid the decay of the femtosecond and picosecond pulses in the course of amplification. Such complications of the schemes for the generation of high-energy pulses account for the interest in the intracavity methods for an increase in the pulse energy in the absence of the additional amplification stages. A method based on an increase in the cavity length was successfully employed in [12–14, 16, 18–21]. However, the experiments show that the stability of the ultralong lasers with the NPE mode locking is lower than the stability of the short lasers on the time scale of the round trip of the cavity and on long time scales (about one hour). Indeed, we obtain the bell-shaped laser spectra using the long cavities (see, for example, [18]), which indicate the stochastic regime of the generation of wave packets. In contrast to the operation of the short lasers, the tuning of the polarization elements does not allow the transition of the ultralong lasers to the regime of stable lasing, which is characterized by the spectrum with steep edges. The experimental data are in agreement with the results of the numerical simulation performed using the method from [19, 22]. In the experiments with cavity lengths of greater than 100 m, we fail to observe the stable single-pulse lasing, which is characterized by the bell-shaped ACF and the spectrum with steep edges.

Another aspect of the instability of the ultralong lasers is the spontaneous suppression of the regime of lasing (stability on long time scales). In comparison with the short lasers, the ultralong lasers exhibit more complicated tuning of the polarization elements needed for the realization of the regime and the subsequent spontaneous suppression of lasing over a relatively short time interval (no greater than a few hours). The evident physical effects that lead to the above instability are the temperature drift and polarization instability in long fibers along with the inelastic deformations of the amorphous optical fiber in the polarization controllers.

LASERS WITH MEDIUM CAVITY LENGTHS

Both short (with lengths of several meters) and ultralong (with lengths of greater than 1 km) mode-locked NPE lasers exhibit significant disadvantages with respect to practical applications: the short laser generate only low-energy pulses and the ultralong lasers fail to provide the stable single-pulse lasing.

In this regard, it is expedient to analyze the mode locking in the lasers with intermediate cavity lengths ranging from several tens to several hundreds of meters.

The experiments yield gradual rather than qualitative variations in the parameters of lasers at intermediate cavity lengths. In particular, the pulse energy

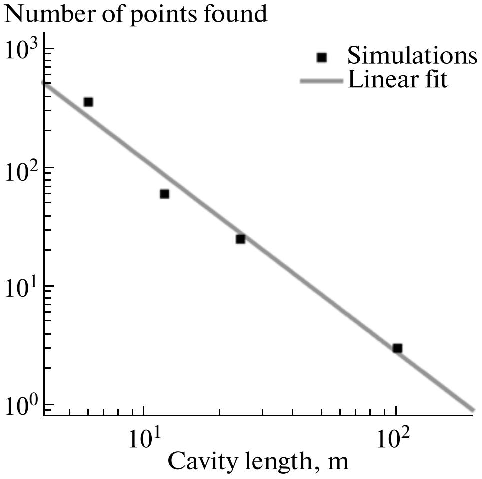

Fig. 4. Plot of the number points in the space of parameters of the polarization elements that correspond to the stable single-pulse lasing in the numerical simulation vs. the cavity length.

increases with cavity length (Fig. 3). The spread of values in Fig. 3 corresponds to the energy intervals that were obtained in the numerical simulation for various tunings of the polarization elements. It is seen that the mean energy almost linearly increases with an increase in the cavity length for both the stable single-pulse lasing (lower dots) and the stochastic regime (upper dots). For almost all of the fixed cavity lengths, the mean pulse energy in the stable regime is less than the mean pulse energy in the stochastic regime in qualitative agreement with the experimental data.

Another parameter that determines the working characteristics of the passively mode-locked NPE laser is the probability of the activation of mode locking at random parameters of the polarization controllers. Figure 4 shows the results of simulation and demonstrates the number of the sets of the polarization parameters that correspond to the stable single-pulse lasing versus the cavity length. The simulation shows that the probability of the activation of the stable single-pulse mode-locked lasing monotonically decreases with increasing cavity length. For a cavity length of 100 m, only three points that correspond to the stable pulsed lasing are found in the space of parameters of the polarization elements. The numerical simulation yields the absence of the stable single-pulse lasing for cavity lengths of greater than 100 m.

Note that a decrease in the probability of the mode-locking in the numerical simulation is in agreement with a decrease in the stability of the corresponding regime on long time scales in the experiments. Indeed, a relatively low probability of the stable regime corresponds to a relatively small size of the domain of stable lasing. Even minor temperature fluctuations or fluctuations of the parameters of polarization elements due to the deformation of fiber are sufficient for the suppression of the corresponding regime of lasing in agreement with the experimental data.

CONCLUSIONS

We generalize the results on the regimes of the lasers with the NPE mode locking in short (several meters) and ultralong (more than 1 km) cavities and present new data for the intermediate cavity lengths. The results indicate a gradual decrease in the stability of lasing with an increase in the cavity length. Thus, the stable single-pulse mode-locked lasing can hardly be achieved in the NPE laser with a cavity length of greater than 100 m. However, the experiments from [24] yield the single-pulse lasing in the cavity with a length of greater than 1 km when the saturable absorber is used for mode locking.

Note that the generation of picosecond trains consisting of the stochastic femtosecond pulses which predominantly corresponds to relatively large cavity lengths can be interesting for several applications, in particular, the Raman amplification with backward pumping [25, 26].

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