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Pulse dynamics in a passively mode-locked chirped-pulse fiber laser

B. Ortaç · M. Plötner · J. Limpert · A. Tünnermann

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Abstract We report experimental and numerical results on the new pulse dynamics in a passively mode-locked ytterbium-doped fiber laser operating in the chirped-pulse regime. Due to the negligible nonlinearity of added highly-positive GVD segment in the purely-normal-dispersion regime, highly-positive chirped pulses can be formed through weak intra-cavity temporal and spectral breathing. Numerical simulations reveal intra-cavity pulse evolution with local temporal stretching phenomena and pulse shaping properties.

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Passively mode-locked laser systems are attractive scientific platforms to generate ultra-short pulses as a versatile tool for many applications [1] and to study dissipative nonlinear optical phenomena where the nonlinear dynamics of the optical field is primarily governed by its energy exchange with environment [2]. The dispersion issue in fiber-based mode-locked lasers plays an important role on pulse shaping and different pulse dynamics have been reported in various regimes of operation with a wide variety of pulse shapes. The fundamental soliton ($sech^2$) transform-limited pulses in the purely-anomalous group velocity dispersion (GVD) fiber have been generated [3]. The dispersion-managed soliton regime operating in the anomalous net-cavity dispersion presents similar spectral and temporal pulse shape with weak temporal and spectral breathing inside the resonator [4]. Approaching the zero net-cavity dispersion, the stretched-pulse regime is observed and the Gaussian-shaped pulse width experiences relatively large variations per cavity round trip [5]. In the normal-dispersion regime, the monotonic frequency chirp evolution of the pulse is obtained by suppressing wave-breaking phenomena in the normal GVD cavity segment [6] and in a special case of this regime, the so-called similarition laser, and the output pulses are linearly chirped with a parabolic temporal intensity profile [7]. Ultra-short pulse generation has been recently realized in the purely-normal-dispersion regime. The spectral filtering is applied to enhanced self-amplitude modulation and a higher tolerance of accumulated nonlinear phase shifts has been obtained [8]. The implementation of low nonlinearity fiber designs has been demonstrated as a further regime in an all-normal configuration with a real saturable absorber and nonlinear effects are significantly reduced; the self-consistency could be achieved by gain filtering and nonlinear absorbing mechanisms with very low intra-cavity pulse breathing [9]. A novel scheme has been developed by incorporating a large positive GVD segment with negligible nonlinearity in the purely-normal-dispersion laser configuration [10]. The main difference from the fiber-based system to bulk-based counterparts [11] arises, being that the stable mode-locking operation is demonstrated with a considerably larger amount of linear GVD cavity element in the chirped-pulse fiber oscillator concept.

In this Letter, we report on a new nonlinear optical dissipative system in the form of a mode-locked fiber laser operating in a highly-positive dispersion regime. A segment possessing a large amount of positive GVD and negligible

B. Ortaç (✉) · M. Plötner · J. Limpert · A. Tünnermann
Institute of Applied Physics, Friedrich Schiller University Jena, Jena, Germany
e-mail: buelend.ortac@uni-jena.de
Fax: +49-3641-947802

A. Tünnermann
Fraunhofer Institute for Applied Optics and Precision Engineering, Jena, Germany

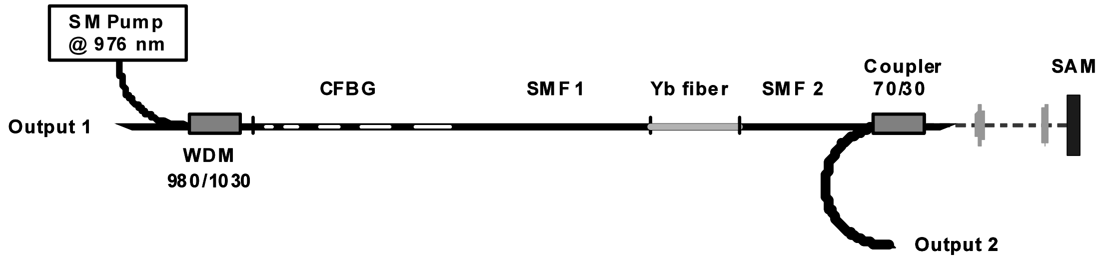

Fig. 1 Schematic representation of the passively mode-locked Yb-doped all-polarization-maintaining chirped-pulse fiber laser

nonlinearity is added to an all-normal mode-locked fiber laser. A new pulse dynamics is demonstrated experimentally and numerically for the first time, which on average generates longer positively-chirped pulses. The pulse evolution is characterized by weak intra-cavity temporal and spectral breathing with local temporal stretching phenomena.

The experimental setup of the passively mode-locked chirped-pulse fiber laser is illustrated in Fig. 1. All-fiber components are based on the polarization-maintaining single-clad concept. A section of 30 cm highly ytterbium-doped fiber is spliced between different lengths of passive fibers (SMF1 = 1.2 m and SMF2 = 0.5 m). One of the key elements in this cavity is the CFBG providing positive dispersion together with negligible nonlinearity. The dispersion and the peak reflectivity of CFBG have been measured to be 0.19 ps^2 (66% of total-cavity dispersion) and 27% with Gaussian-like spectral bandwidth of 16 nm, respectively. Several attractive properties of the CFBG can be employed as a highly-positive dispersive element to stretch the pulse during its propagation and an output coupler (output 1) to study the laser operation. Passive mode-locking is achieved by using a saturable absorber mirror (SAM) similar to that employed in [10]. To study intra-cavity pulse dynamics and to select the single-polarization propagation in this laser configuration additional fiber-based coupler (output 2) is inserted. The SAM and fiber-based output coupler are placed at the end of the linear cavity.

The self-starting and stable mode-locked operation is obtained by optimizing the saturation threshold on the SAM for an adequate launched pump power. We investigate the intra-cavity pulse evolution in this configuration and the experimental results obtained at the two output ports are summarized in Fig. 2. The optical spectrum, shown in Fig. 2(a), obtained for a pump power of 155 mW, possesses the same characteristics: steep spectral edges. The central wavelength is 1033.5 nm and the 10-dB and 3-dB bandwidths of the optical spectra at the output 1 (and output 2) are 2.4 nm (2.45 nm) and 1.79 nm (2.05 nm), respectively. The asymmetric spectral behavior can be attributed, at first, to the finite temporal response of the SAM [12] and Bragg reflector of SAM, gain dynamic and transmission properties of fiber-based cavity element (CFBG and coupler). An additional residual low frequency intensity modulation appears in the optical spectrum, which is very different than that reported in [6] where the presence of a high frequency intensity modulation is attributed to interference effects by polarization mode mixing and intra-cavity splice issues.

The autocorrelation traces obtained directly at the laser outputs are shown in Fig. 2(b). The positively chirped output pulses are well fitted with a Gaussian shape with pulse durations of 21.8 ps and 19 ps. These pulses are externally compressed by a linear process outside the cavity (not shown in Fig. 1). The autocorrelation traces of the externally compressed pulse at both outputs are present with the same width of 2.1 ps (FWHM), which corresponds to a pulse duration of 1.37 ps. The transform-limited pulse duration is calculated to be 1.11 ps, which indicates that the pulses can be compressed down to near transform-limited pulse duration. The anomalous dispersion necessary for the compression of the chirped output pulses at the two output ports by the grating pair is more than $-7.7\ ps^2$. This indicates that the laser generates highly-positive chirped output pulses. We measured the average output powers of 33 mW and 3 mW at output 1 and 2, which corresponds to an energy per pulse of 750 pJ and 68 pJ.

We have experimentally presented the main properties of pulse evolution at the two different output ports. In order to obtain a better understanding of the pulse generation and the intra-cavity evolution of the highly chirped pulses in the above-reported laser configuration the laser has been studied numerically. Due to the single-polarization state propagation inside the cavity, the simple scalar numerical simulation based on a non-distributed model solving all parts described by one nonlinear Schrödinger equation is investigated [13]. In the simulation the parameters for the cavity elements match those of the experimental setup. This includes the action of the output coupling, the saturable absorber, the active and passive fibers and an additional positive GVD segment with negligible nonlinearity and Gaussian-shaped spectral filter profile. The absorption in the semiconductor was described by the rate equation model [14]. The saturation energy due to the limited pumping is set in the model in such a way that the extracted energy is similar to that

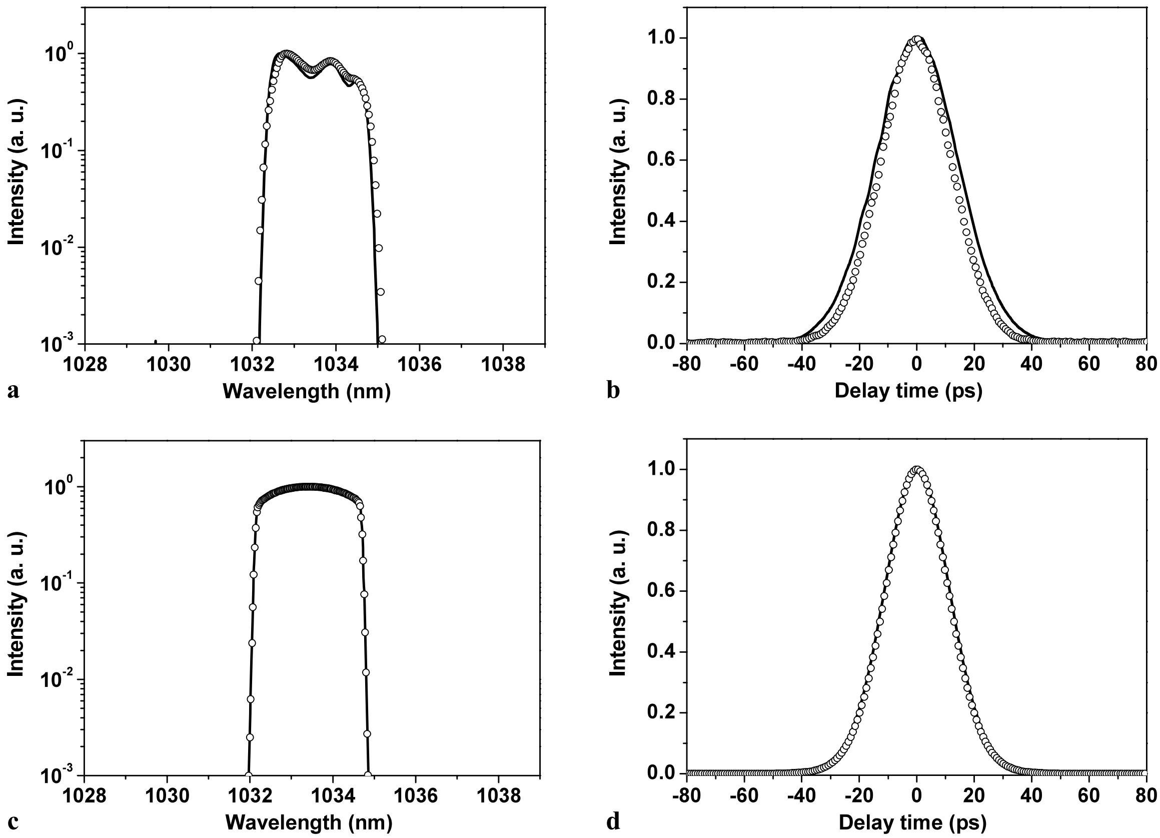

Fig. 2 Results of experimentally measured optical spectrum (**a**) and autocorrelation trace of chirped pulses (**b**) from the fiber oscillator compared to numerical simulations (**c–d**). *Solid line*: output port 1, *open circle*: output port 2

obtained in the experiments. The exact stable solution, obtained using quantum noise as the initial condition, is compared with the experimental results. Figure 2 also shows the spectral and temporal results of the numerical simulations obtained at the two output ports. One can clearly see that the pulse shows a steeply edged spectral profile as measured experimentally, as can be seen in Fig. 2(c) at both outputs. The spectral bandwidths at the output ports 1 and 2 are about 2.55 nm and 2.53 nm. The simulated pulse durations at both output ports are present with the pulse widths of 18.5 ps and 17.8 ps, and the pulse profiles are also best fitted with a Gaussian temporal intensity profile. However, in the chirped-pulse fiber laser presented here, the linear chirp is dominant in the numerical solution and recompression of the pulses close to the transform-limit is possible. The simulated pulse energy, duration, profile and spectral shape with bandwidth present very good agreement with experimental results.

It is therefore of great importance to understand better the physical mechanisms of pulse formation and evolution. To gain insight into the intra-cavity pulse evolution, the spectral and temporal characteristics of one cavity round-trip of the pulse (stable solution after convergence) are shown in Fig. 3. As discussed above, we obtained positively chirped

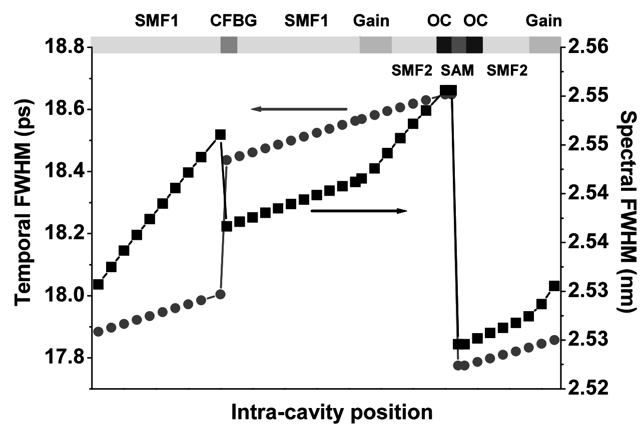

Fig. 3 Simulation of the intra-cavity pulse evolution of the mode-locked chirped-pulse fiber laser in the temporal and spectral domain. OC: Output coupling

output pulses at both output ports. It should be mentioned that there is no negative GVD element implemented intra-cavity and the pulses are always positively chirped inside the cavity. The pulse duration increases monotonically within the gain fiber and passive fibers. For the first time, we observe the local pulse stretching phenomena in the CFBG segment. The total pulse shortening effect occurs in the SAM segment by the nonlinear absorbing mechanism. In the spectral domain, spectral broadening via self-amplitude modulation (SPM) can be observed during propagation through the fiber. An additional pulse shaping mechanism by spectral filtering is caused by the reflectivity properties of the CFBG, however, according to the simulation; this filtering is not needed for self-consistency. The main spectral shortening effect occurred in the SAM segment. In addition, the simulation shows that spectral shaping by the gain profile is present even at that narrow spectral bandwidth. Finally, self-consistency could be achieved by the balance between the SAM nonlinearity, CFBG properties and the nonlinearity into the gain and passive fibers. With these experimental and numerical results we can conclude that the pulse dynamics in the new regime reveals weak intra-cavity temporal and spectral breathing leading to on average longer positively chirped pulses and output spectra and pulse profile present similar shapes at two opposite output ports.

In conclusion, we have demonstrated intra-cavity pulse dynamic investigations of passively mode-locked environmentally-stable Yb-doped fiber laser operating in the chirped-pulse regime. Detailed experimental and numerical studies of the main properties of the pulse shaping mechanism are presented. A highly-positive GVD negligible nonlinearity segment is implemented in the all-normal fiber laser concept and the local temporal stretching phenomena is observed during the intra-cavity propagation. The additional pulse shaping element is provided by using the reflectivity properties of the same element, i.e. the CFBG. The chirped-pulse mode-locked fiber laser generates highly-positively-chirped pulses with very weak intra-cavity temporal and spectral changes, and consequently, on average longer pulses and lower peak powers. A new design of mode-locked fiber laser systems is revealed. The interesting feature of the presented approach is that the limitations induced by the nonlinear effects could be reduced by scaling down the peak intensity inside the fiber core by stretching the pulse during the intra-cavity propagation leading to the possibility of energy scaling [15].

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