High-power femtosecond Yb-doped single-polarization photonic crystal fiber laser

B. Ortaç[1], C. Lecaplain[1, 2], A. Hideur[1, 2], J. Limpert[1], and A. Tünnermann[1, 3]

[1]Friedrich-Schiller University, Institute of Applied Physics, Jena, Germany.
[2] Groupe d'Optique et d'Optronique, CORIA UMR 6614, Université de Rouen, Saint Etienne du Rouvray Cedex, France.
[3]Fraunhofer Institute for Applied Optics and Precision Engineering, Jena, Germany.

ABSTRACT

We report, to the first time to our knowledge, on a passively mode-locked single-polarization single-transverse-mode large-mode-area photonic crystal fiber laser operating in the dispersion compensation free regime. In the single-pulse regime, the laser generates 1.6 W of average power with 3.7 ps pulses at a repetition rate of 63 MHz, corresponding to a pulse energy of 25 nJ. Stable and self-starting operation is obtained by adapting the spot size at the saturable absorber mirror to the pulse evolution in the low-nonlinearity fiber. The pulses are compressible down to 750 fs. The presented approach demonstrates the scaling potential of fiber based short pulse oscillators towards high-power ultra-compact all-fiber environmentally-stable configuration.
Keywords: Mode-locked fiber laser, femtosecond pulse generation, power and energy scaling, single-polarization fiber.

1. INTRODUCTION

High-energy and high-average-power ultra-short pulse laser sources have been an interesting research area and fiber based short-pulse lasers gain increasing interest over the recent decade. Rare-earth-doped fiber lasers present unique properties due to the diffraction-less propagation and the absence of thermo-optical problems. Due to the light confinement, fiber lasers offer the remarkable opportunity to develop environmentally stable laser sources making them ideal candidates for a number of industrial and scientific applications.

The pulse energy achievable in mode-locked fiber laser systems is limited by nonlinear effects occurring during propagation through the fiber, mainly Kerr-nonlinearity. Different approaches of mode-locked fiber laser configurations have been developed to obviate this limitation. Dispersion-managed mode-locked fiber lasers have attracted much interest due to the reduced peak power inside the fiber compared to the conventional soliton regime [1]. This concept is implemented in operation regimes such as stretched-pulse [2] and self-similar [3], where the pulse width experiences large variations per cavity round trip.

The development of mode-locked fiber lasers made of purely normal dispersion fibers to achieve higher pulse energies has attracted much attention in the recent few years [4-8]. In particular, it has been demonstrated that a spectral filter could stabilize high-energy pulses in an Yb-fiber laser leading to the achievement of more than 20 nJ energy with femtosecond pulses [8]. However, pulse energy scaling capabilities of these fiber lasers is limited because of the small fiber core size and hence the strong accumulated nonlinearity. As known from ultra-fast fiber amplifier systems a reduction of nonlinearity and consequently potential performance enhancement can be obtained by the enlargement of the fiber mode area. Mode-locked fiber lasers employing low-numerical aperture large-mode-area (LMA) step-index fibers, forced to operate in single-transverse mode have been reported. However, the pulse quality and stability of operation was not satisfying due to mode-coupling in the high-order transverse modes. More recently, significant energy scaling in mode-locked fiber lasers have been demonstrated using LMA photonic crystal fibers [9-11]. Indeed, passively mode-locked fiber lasers operating in the anomalous dispersion regime [9] as well as in the purely normal dispersion regime [10-11] have been reported with exceptional performances in terms of pulse energy and peak power. Additionally, these lasers use only a semiconductor saturable absorber mirror as the mode-locking mechanism leading to very compact designs. However, in spite of the short typical lengths (about a meter) used in these experiments, the linear birefringence seems to play a key role and polarization effects on pulse shaping have been observed [10].

Fiber Lasers V: Technology, Systems, and Applications, edited by Jes Broeng, Clifford Headley,
Proc. of SPIE Vol. 6873, 687321, (2008) · 0277-786X/08/$18 · doi: 10.1117/12.763621

It is well known, that the linear birefringence is sensitive to the thermal and mechanical perturbations which could induce random birefringence changes in the fiber which are sources of environmental instabilities in mode-locked fiber lasers. One approach to compensate for linear polarization drifts in the fiber is the use of a Faraday rotator mirror [12, 13]. The most common approach consists to use polarization-maintaining (PM) fibers with the light polarized only along the slow axis. Environmentally-stable, partly in an all-fiber configuration, mode-locked PM core-pumped single-mode fiber lasers have been reported at various operation wavelengths [14-18]. The other environmentally-stable fiber laser configuration, so-called sigma cavity design, consists in a PM fiber inserted in the ring segment of a sigma cavity and a non-PM fiber introduced in the linear section with Faraday mirror rotator [19-20].

Recently, polarization maintaining LMA photonic crystal fibers have been demonstrated using the well-known technique of stress-applying parts (SAP) inside the fiber [21, 22]. In addition, it has been shown that using a particular design that comprises the stress-applying elements as part of the photonic cladding could result in single-polarization propagation over a large spectral range [22]. Indeed, in such design light is confined by both parts of the photonic cladding: the air holes and the index matched regular array of SAPs. The resulting birefringence is enough to split two polarization states of the weakly guided fundamental mode in that way, that the effective index of one polarization is below the cladding index, thus, resulting in a single polarization LMA fiber.

In this contribution, we report the first demonstration of a passively mode-locked single-polarization single-transverse-mode LMA photonic crystal fiber laser operating in the dispersion compensation free regime. A semiconductor saturable absorber mirror (SAM) is used for passive mode-locking. In the single-pulse regime, the laser generates 1.6 W of average power at a repetition rate of 63 MHz, corresponding to a pulse energy of 25 nJ. Positively-chirped pulses with 3.7 ps duration are compressed down to near transform-limited duration of 750 fs. Numerical simulations reveal that stable-pulse formation inside the cavity is governed by the interplay between the SAM nonlinearities, the gain filtering and Kerr-nonlinearities in the gain fiber.

2. EXPERIMENTAL SETUP

The experimental setup of the fiber oscillator assembled in the sigma cavity configuration is shown in Fig. 1. The gain fiber is an Yb-doped air-clad single-polarization photonic crystal fiber [22]. A cross section of this fiber is shown in reference 23. The intrinsically single-mode core possesses a core diameter of 40 µm and the inner cladding has a diameter of 170 µm with a numerical aperture as high as 0.62 at 975 nm. At that wavelength the pump light absorption is 16 dB/m resulting in a very short fiber length of just 1.2 m. The single-polarization window of this fiber is about 300 nm centered at 1 µm. In an amplifier configuration, the beam quality is characterized to M^2=1.17 and the degree of polarization to 98% [22]. To avoid undesired parasitic reflections, the fiber end facets are angle-polished. The fiber laser

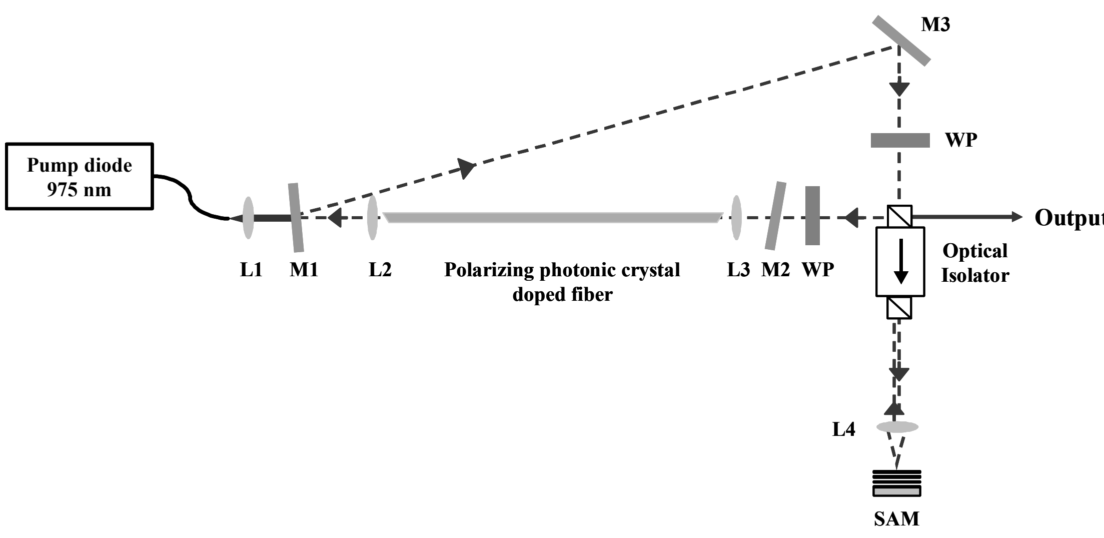

Figure 1. Schematic representation of the mode-locked Yb-doped single-polarization fiber laser. L: Lens, M1 and M2: Dichroic mirrors, M3: High reflection mirror, WP: Wave plate and SAM: Saturable absorber mirror.

is pumped from one side by a fiber-coupled laser diode. The laser beam is collimated inside the cavity with adaptive lens system (not shown here). A dichroic mirror M1 is used to separate the pump beam from the laser emission. A second dichroic mirror M2 blocks unabsorbed pump radiation. The ytterbium-doped fiber is placed in the ring section of the cavity. An optical isolator assures the unidirectional propagation of the laser light inside the resonator. The reflected polarization of the polarization beam splitter of the isolator serves as the output. By means of a quarter-wave plate between the isolator and the fiber, the output coupling (OC) ratio is controlled. An additional half-wave plate is implemented to ensure excitation of the slow axis (guiding axis) of the fiber. Passive mode-locking is achieved employing a saturable absorber mirror (SAM) placed at the end of the linear section of the sigma cavity. The low-intensity absorption of the SAM at around 1040 nm is ~15 %, the modulation depth ~10 % and the saturation fluence as high as 70 μJ/cm^2 with a relaxation time of ~500 fs. No dispersion compensation element and no additional spectral filter element are introduced into the setup. The total second-order cavity dispersion is about + 0.03 ps^2 at 1038 nm, mainly by the gain fiber. The fiber laser directly generates positively-chirped picosecond pulses, which have been externally compressed by a 1250 lines/mm transmission grating pair (not shown in the figure).

3. EXPERIMENTAL AND NUMERICAL RESULTS

Stable mode-locked operation is obtained by optimizing the saturation threshold on the SAM. However, when the mode-locking threshold is achieved, the quarter wave-plate inside the laser has been adjusted to a high output coupling ratio in order to avoid damage of the SAM and extract higher pulse energies. It should be mentioned that due to single-polarization of employed fiber passive mode-locking can not be achieved by nonlinear polarization rotation. Above the mode-locking threshold (at about 550 mW average output power) the laser delivers a single pulse train with a repetition rate of 63 MHz. The average output power can be increased to 1.6 W, which results in an energy per pulse of 25 nJ, before instabilities were observed. Further, the laser system presented is intrinsically environmentally stable due to the employment of single polarizing fiber. The mode-locked laser operation is very stable over several hours and self-starting with the same pulse characteristics (spectrally and temporally) for equal pump powers. The operation of the laser is also characterized by very low amplitude noise. Figure 2 shows the typical emission spectrum at highest pulse energy which is characterized by steep edges. The center wavelength is 1038.8 nm and the spectral bandwidth (7dB) is 5.45 nm.

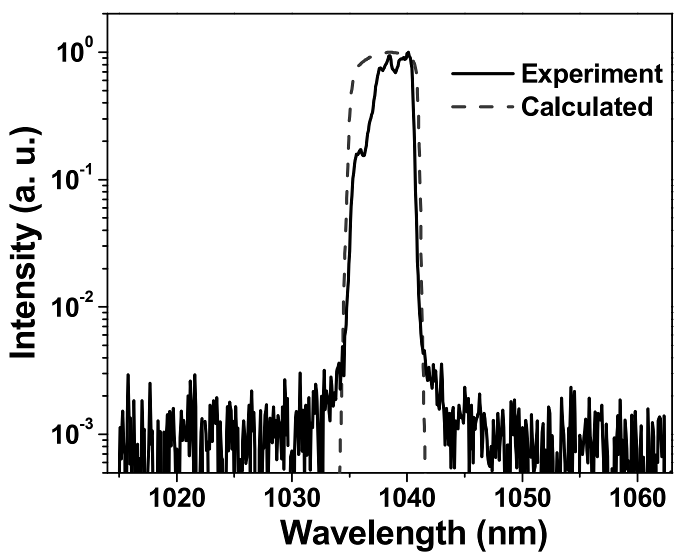

Figure 2. Measured optical spectrum from fiber oscillator (solid line) compared to spectrum at the output from numerical simulation (dashed line).

The autocorrelation trace obtained directly at the laser output is shown in Fig.3. The clean positively-chirped output pulses present an autocorrelation width of 5.3 ps (FWHM) which corresponds to pulse duration of 3.7 ps assuming a deconvolution factor of 1.4. Single-pulse operation is proven by using a background-free autocorrelator with a scanning range of 150 ps and a 200 ps rise time photo-diode. In the purely normal dispersion fiber laser studied here, pulse

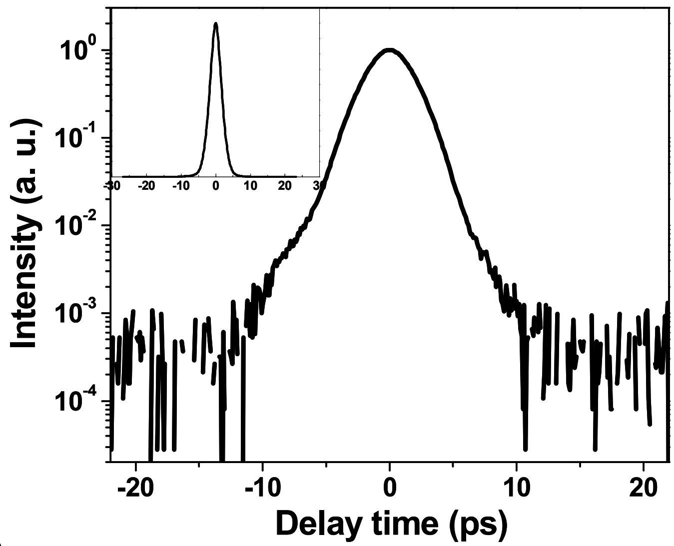

Figure 3. Autocorrelation trace of chirped pulses observed directly at the laser output.

shaping is governed by the SAM nonlinearities. So, the asymmetric spectrum presented in Fig. 2 could be attributed to the temporal and spectral response behavior of the SAM.

The output pulses are externally compressed by a transmission-grating pair and the measured autocorrelation trace is shown in Fig. 4. Assuming a deconvolution factor of 1.4 (motivated by numerical simulations discussed below) a pulse duration as short as 750 fs (Autocorrelation (AC) width of 1.05 ps) has been obtained. The autocorrelation width of the transform-limited pulse calculated from the power spectrum shows the same width (FWHM), which indicates that the linear chirp, is dominant. The pedestal structures in the AC can be attributed to the steep edges of the spectrum.

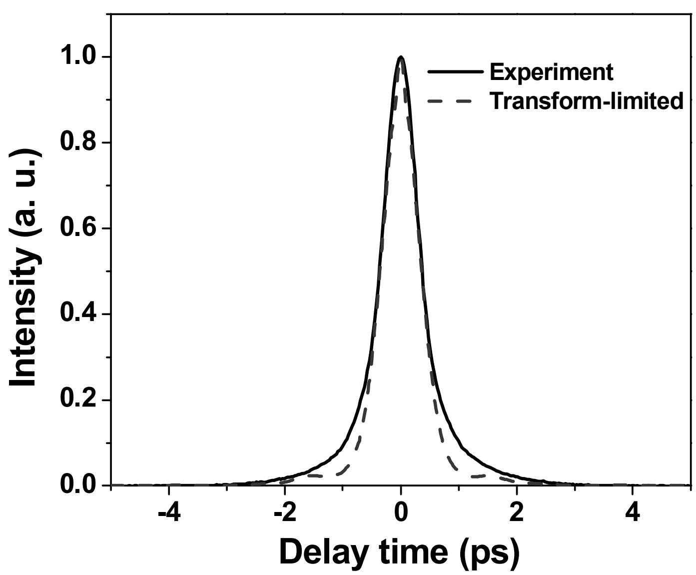

Figure 4. Autocorrelation trace of the dechirped pulses (solid line) compared to the AC of transform-limited pulses (dashed line).

The single-polarization fiber laser presented above constitutes an ideal configuration to perform numerical simulations since the single polarization state propagating inside the fiber could be described in the frame of a scalar model of one non-linear Schrödinger equation. To study the intra-cavity pulse dynamics in this laser configuration, numerical simulation based on a non-distributed model solving all parts described by Schrödinger equation with the split- step Fourier algorithm is investigated [24]. As we expect generation of picosecond pulses inside the cavity, we can ignore higher-order dispersion terms in the numerical model. The saturation energy due to limited pumping is set to extract an energy similar to experiment at a high output-coupling ratio of 80 %. The simulation starts from quantum noise and after convergence, the intra-cavity pulse evolution is calculated. The result is shown in Fig. 5, where the effect of the OC and the SAM is done in a single step and the propagation through the 1.2 m long gain fiber is scaled to the residual cavity. The nonlinear absorbing mechanism of the SAM results in a pulse shortening as well as a reduction of spectral width.

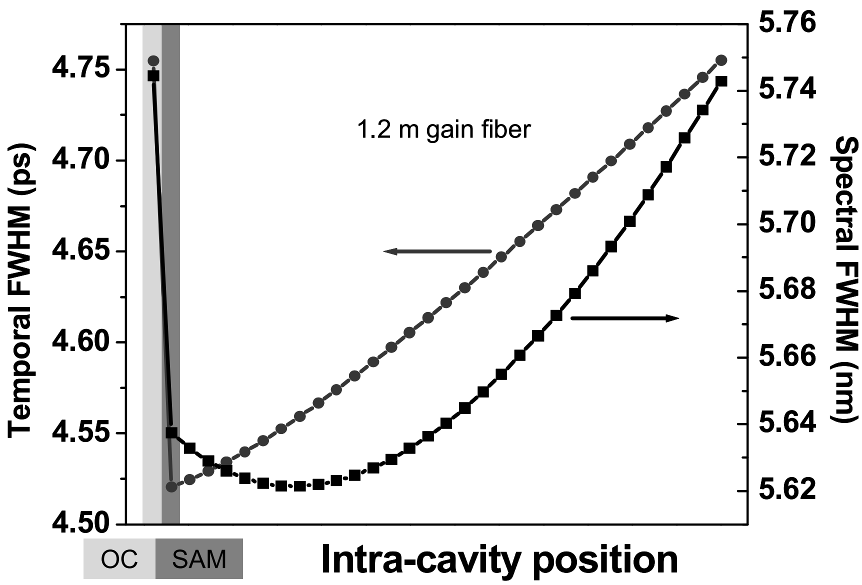

Figure 5. Simulation of the intra-cavity pulse evolution of dispersion compensation free mode-locked fiber laser in the temporal and spectral domain. OC: Output coupling and SAM: Saturable absorber mirror.

As revealed by the simulation, the pulses are always positively chirped inside the cavity with only one minimum located at the entrance of the fiber and pulse duration increases monotonically during the amplification in the gain fiber. In addition, gain filtering can be recognized even at that narrow spectral bandwidth. Spectral broadening via self-amplitude modulation (SPM) can be observed after sufficient peak power is reached during the amplification. Finally, the self-consistency could be achieved by the balance between the SAM nonlinearity and the gain filtering. Figure 5 discusses the temporal and spectral results of the numerical simulation of the intra-cavity pulse evolution. The simulated pulse duration at the output port is 4.75 ps (AC width of 6.71 ps). However, in the single-polarization fiber laser presented here, the linear chirp is dominant in the numerical solution and recompression of the pulses close to transform-limited should be possible. The pulse spectrum agrees as well in width (5.74 nm) and shape with the experimentally measured spectrum (see Fig. 2).

4. CONCLUSION

In conclusion, we have demonstrated, for the first time to our knowledge, an environmentally-stable and self-starting dispersion compensation free passively mode-locked single-polarization single-mode large-mode-area photonic crystal fiber laser. The laser generates 1.6 W of average power at a repetition rate of 63 MHz, corresponding to a pulse energy of 25 nJ. Positively-chirped pulses are emitted with 3.7 ps duration and could be externally compressed down to near transform-limited duration of 750 fs. The numerical simulations reflect accurately the experimental results. The presented approach reveals the capability of fiber based environmentally stable high-power short pulse sources.

REFERENCES

1. K. Tamura, L. E. Nelson, H. A. Haus, and E. P. Ippen, “Soliton versus nonsoliton operation of fiber ring lasers,” Appl. Phys. Lett., **64**, 149 (1994).
2. K. Tamura, E. P. Ippen, and H. A. Haus, “Pulse dynamics in stretched-pulse fiber lasers,” Appl. Phys. Lett., **67**, 158 (1995).
3. F. Ö. Ilday, J. Buckley, W. Clark, and F.W. Wise, “Self-Similar Evolution of Parabolic Pulses in a Laser,” Phys. Rev. Lett., **91**, 213902 (2004).
4. R. Herda and O. G. Okhotnikov, “Dispersion compensation-free fiber laser mode-locked and stabilized by high-contrast saturable absorber mirror,” IEEE J. Quantum Electron. **40**, 893 (2004).
5. L. M. Zhao, D. Y. Tang, and J. Wu, “Gain-guided soliton in a positive group-dispersion fiber laser,” Opt. Lett. **31**, 1788-1790 (2006).
6. A. Chong, J. Buckley, W. Renninger, and F. Wise, “All-normal dispersion femtosecond fiber laser,” Opt. Express **14**, 10095 (2006).
7. L. M. Zhao, D. Y. Tang, H. Zhang, T. H. Cheng, H. Y. Tam, and C. Lu, “Dynamics of gain-guided solitons in an all-normal-dispersion fiber laser, ” Opt. Lett. **32**, 1806-1808 (2007).
8. A. Chong, W. H. Renninger, and F. W. Wise, “All-normal-dispersion femtosecond fiber laser with pulse energy above 20nJ,” Opt. Lett. **32**, 2408-2410 (2007).
9. B. Ortaç, J. Limpert, and A. Tünnermann, “High-energy femtosecond Yb-doped fiber laser operating in the anomalous dispersion regime,” Opt. Lett. **32**, 2149 (2007).
10. C. Lecaplain, C. Chédot, A. Hideur, B. Ortaç, and J. Limpert, “High-power all-normal dispersion femtosecond pulse generation from a Yb-doped large-mode-area microstructure fiber laser,” Opt. Lett. **32**, 2738 (2007).
11. B. Ortaç, O. Schmidt, T. Schreiber, J. Limpert, A. Tünnermann, and A. Hideur, “High-energy femtosecond Yb-doped dispersion compensation free fiber laser,” Opt. Express **15**, 10725 (2007).
12. M. E. Fermann, L. M. Yang, M. L. Stock, and M. J. Andrejco, “Environmentally stable Kerr-type mode-locked erbium fiber laser producing 360-fs pulses,” Opt. Lett. **19**, 43 (1994).
13. M. E. Fermann, D. Harter, J. D. Minelly, and G. G. Vienne, “Cladding-pumped passively mode-locked fiber laser generating femtosecond and picosecond pulses,” Opt. Lett. **21**, 967 (1996).
14. E. A. De Souza, C. E. Soccolich, W. Pleibel, R. H. Stolen, J. R. Simpson, and D. J. DiGiovanni, “Saturable absorber mode locked polarisation maintaining erbium-doped fibre laser,” Electron. Lett. **29**, 447 (1993).
15. J. W. Nicholson, and M. Andrejco, “A polarization maintaining, dispersion managed, femtosecond figure-eight laser,” Opt. Express **14**, 8160 (2006).
16. I. Hartl, G. Imeshev, L. Dong, G. C. Cho, and M. E. Fermann, “Ultra-compact dispersion compensated femtosecond fiber oscillators and amplifiers,” CLEO, Baltimore, paper CThG1, May 2005.
17. C. K. Nielsen, B. Ortaç, T. Schreiber, J. Limpert, R. Hohmuth, W. Richter, and A. Tünnermann, “Self-starting self-similar all-polarization maintaining Yb-doped fiber laser,” Opt. Express **13**, 9346 (2005).
18. B. Ortaç, M. Plötner, T. Schreiber, J. Limpert, and A. Tünnermann, “Experimental and numerical study of pulse dynamics in positive net-cavity dispersion mode-locked Yb-doped fiber lasers,” Opt. Express **15**, 15595 (2007).
19. T. F. Carruthers, I. N. Duling, and M. L. Dennis, “Active-passive modelocking in a single-polarisation erbium fibre laser,” Electron. Lett. **30**, 1051 (1994).
20. D. J. Jones, L. E. Nelson, H. A. Haus, and E. P. Ippen, “Diode-pumped environmentally stable stretched-pulse fiber laser, ” IEEE J. Selected Topics in Quantum Electron. **3**, 1076 (1997).
21. T. Schreiber, H. Schultz, O. Schmidt, F. Röser, J. Limpert, and A. Tünnermann, “Stress-induced birefringence in large-mode-area micro-structured optical fibers, ” Opt. Express **13**, 3637 (2005)
22. T. Schreiber, F. Röser, O. Schmidt, J. Limpert, R. Iliew, F. Lederer, A. Petersson, C. Jacobsen, K. P. Hansen, J. Broeng, and A. Tünnermann, “Stress-induced single-polarization single-transverse mode photonic crystal fiber with low nonlinearity,” Opt. Express **13**, 7621 (2005).
23. S. Klingebiel, F. Röser, B. Ortaç, J. Limpert, and A. Tünnermann, “Spectral beam combining of Yb-doped fiber lasers with high efficiency,” J. Opt. Soc. Am. B **24**, 1716 (2007).
24. T. Schreiber, B. Ortaç, J. Limpert, and A. Tünnermann, “On the study of pulse evolution in ultra-short pulse mode-locked fiber lasers by numerical simulation,” Opt. Express **15**, 8252 (2007).