Femtosecond Microjoule-Class Ytterbium Fiber Lasers

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Abstract: We report the generation of 830 nJ energy from a mode-locked all-normal dispersion fiber laser featuring large-mode-area photonic crystal fibers. After external compression, 550 fs pulses with 1.2 MW peak power are demonstrated.

OCIS codes: (140.3510) Lasers, fiber, (140.7090) Ultrafast lasers, (060.5530) Pulse propagation and solitons.

1. Introduction

High-power femtosecond laser sources are versatile tools for numerous applications ranging from material processing on a sub-micrometre scale to high-field physics. Developing compact and robust oscillators of high energy femtosecond pulses has therefore generated strong research interest during the past decade leading to significant advances in the field. In particular, impressive performance levels, with microjoules energies and up to hundred watts average powers, have been achieved with thin-disk lasers based on Yb-doped crystals [1]. Another promising solution for energy scaling in mode-locked oscillators is rare-earth-doped fibers. Fiber-based sources exhibit very high gain per pass, excellent thermo-optical properties and high mechanical stability making them very suitable for high-power applications. The fundamental challenge for ultrafast fiber lasers relies on the control of the excessive nonlinearity which hinders a self-consistent pulse evolution at high-energy levels. To some extent, the pulse energy can be scaled by increasing the amount of net positive cavity dispersion, which tends to scale down the peak power inside the fiber core by stretching the pulse during its propagation. This is the principle underlying stretched-pulse [2] and similariton lasers [3]. More recently, new routes for energy scaling of mode-locked fiber oscillators have been opened with the development of all-normal dispersion fiber lasers [4-5]. In order to achieve self-consistent pulse evolution, such lasers need a strong pulse shaping mechanism which could be provided by a passive spectral filter [5] or by combination of self-amplitude modulation with gain filtering [4]. Moreover, the employment of low-nonlinearity large-mode-area photonic crystal fibers (PCF) enables significant power scaling. This has been demonstrated recently in all-normal dispersion laser configurations using different pulse shaping mechanisms [6-8]. Notably, the extension of this approach to photonic crystal rods opens the road for sub-picosecond microjoule-class fiber sources [9-10]. In this communication, we report the generation of high-energy sub-picosecond pulses from a highly normal dispersion fiber laser featuring a Yb-doped rod-type photonic crystal fiber and a large-mode-area photonic crystal fiber. The use of a long passive fiber allows controlling the total net cavity dispersion. Preliminary results show that 13 W of average power at 15.5 MHz repetition rate, corresponding to more than 830 nJ pulses.

2. Experimental setup

The experimental setup of the passively mode-locked fiber oscillator is shown in Fig.1. The gain fiber consists in a 95 cm long Yb-doped photonic crystal fiber with a single-mode core diameter of 80 µm. The laser cavity is mounted in sigma-configuration around a polarization-sensitive isolator. The large-mode-area photonic crystal fiber is cladding-pumped with a fiber-coupled laser diode emitting 50 W at 976 nm A 7 m long passive LMA microstructure fiber with a core diameter of 25 µm is inserted inside the cavity, leading to a total cavity dispersion of about 0.152 ps^2. Insertion of the passive fiber after the output coupling allows controlling both the dispersion and the accumulated nonlinear phase along the cavity. Passive mode locking is achieved using a fast saturable absorber mirror (SAM). The SAM has a low-intensity absorption of 30 %, a modulation depth of 20 %, and a saturation fluence of 120 $\mu J/cm^2$ with a relaxation time of <500 fs. The anti-resonant design of the SAM structure ensures an absorption bandwidth of more than 45 nm.

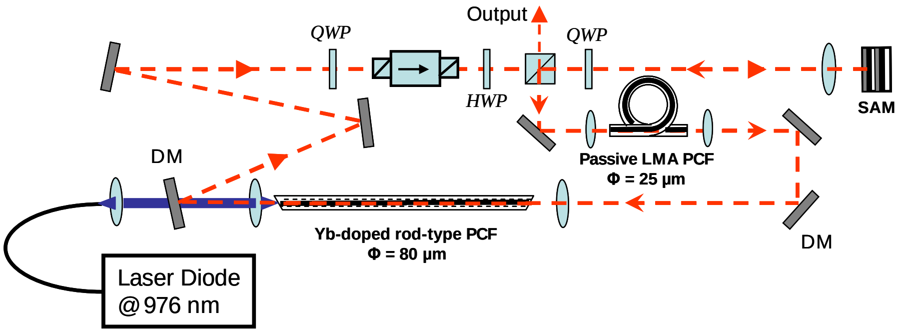

Fig. 1: Experimental setup of the chirped-pulse fiber oscillator

3. Experimental Results

The laser produces a stable self-starting pulse train at a repetition rate of 15.5 MHz. Preliminary results show that 13W of average power, corresponding to 830 nJ, could be achieved. The laser delivers highly-chirped picosecond pulses with about 10 nm spectral widths. The typical laser outputs obtained for an average power of 13 W are shown in Fig. 2. The spectrum is centered around 1028 nm wavelength with a spectral width (FWHM) of 9.3 nm. The optical spectrum presents a typical steep edged shape with a parabolic top. The autocorrelation trace measurement shows that the pulse duration is 27.6 ps assuming a sech² pulse shape [Fig. 2(b)]. The output pulses are extra-cavity dechirped to 550 fs duration using transmission gratings [Fig. 3]. This duration is 1.7 times higher than the transform-limited duration calculated from the spectrum (327 fs). The corresponding peak power is higher than 1.2 MW. The radiofrequency measurements reveal a good amplitude stability of the output pulse train. The pulse to pulse energy fluctuations are estimated to be less that 0.04 %. We note that the current laser performances are only limited by the pump power.

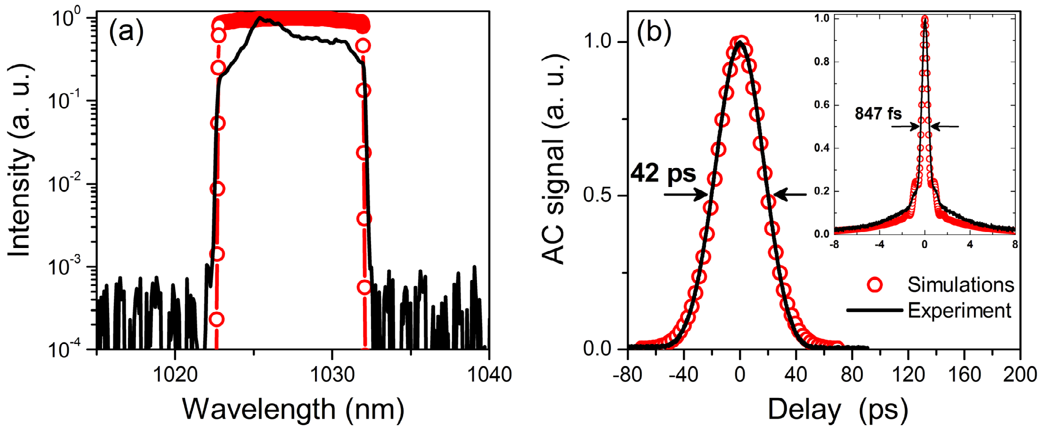

Fig. 2: Typical output spectrum and (b) output pulse autocorrelation. Inset, dechirped pulse autocorrelation

The output pulse parameters are less sensitive to the output coupling ratio compared to the laser configuration based on resonant SESAMs [10]. This suggests that pulse shaping is dominated by the saturable absorber nonlinearity with negligible contribution from nonlinear polarization evolution. To check this hypothesis and study the laser potentialities for energy scaling, numerical simulations were performed considering the laser set-up shown on Fig. 1. Pulse propagation along the gain fiber is described by the extended nonlinear Schrödinger equation which includes the effects of dispersion, Kerr nonlinearity and saturated gain with a finite bandwidth of 45 nm. Absorption of the SAM is described by the rate equation model with a relaxation time of 500 fs. The results obtained for accurate laser parameters are depicted on Fig. 2. Numerical results are in good agreement with experiments and reveal that pulse shaping is dominated by the amplitude modulation provided by the SAM in combination with gain filtering, see Fig. 3. The pulse lengthening happening along the passive fiber is partially compensated by the spectral narrowing happening along the gain fiber. This behavior is governed by the high net cavity dispersion. Indeed, insertion of a long passive fiber enables temporal pulse broadening just behind the gain fiber. This contributes to increase the amplitude modulation induced by gain filtering which acts on highly-chirped pulses. The complete pulse self-consistency is insured by the contribution of the SAM. We note that the monotonic evolution along the passive fiber indicates that the cumulated frequency-chirp is mainly linear. The negligible SPM endured along the gain fiber allows maintaining the linear chirp which is partially removed by the SAM action. The temporal evolution along the cavity resembles that of the self-similar laser [3]. The parabolic-top output spectrum is an additional signature of self-similar pulse evolution (Fig. 2). Moreover, numerical simulations predict that stable pulse solutions do exist for more than 10 µJ intra-cavity pulse energy, revealing a great potential for energy scaling.

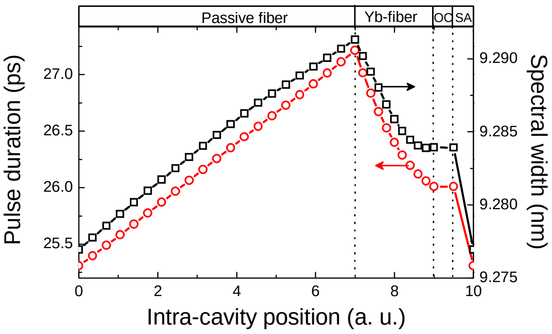

Fig.3 : Pulse evolution inside the cavity in the spectral and temporal domains.

4. Conclusion

In conclusion, we have demonstrated the generation of highly-stretched 27 ps pulses with up to 830 nJ energy from a highly normal dispersion laser featuring large core microstructured fibres. The output pulses are externally dechirped to 550 fs duration with 1.2 MW peak power. Numerical simulations reveal that pulse shaping is dominated by the gain filtering action in combination with the amplitude modulation in the SAM. More details on the energy scaling potential of this source will be discussed in this communication.

Acknowledgement

This work is supported by the Inter Carnot-Fraunhofer program under project APUS and the French Agency for Research under project OFFEMET. We acknowledge support from the Conseil Régional de Haute Normandie.

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