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Monolithic Stabilized Yb-fiber All-PM Laser Directly Delivering nJ-level Femtosecond Pulses

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***Abstract*—We present a monolithic, self-starting, all-PM, stabilized Yb-fiber laser, pulse-compressed in a hollow-core PM photonic crystal fiber, providing the 370 fs pulses of 4 nJ energy with high mode quality.**

I. Introduction

Femtosecond Yb-fiber lasers are emerging as effective and low-cost competitors to their solid-state counterparts, such as Ti:Sa systems. The availability of an all-fiber, monolithic, stable and compact laser, that does not require servicing and can be easily integrated into a custom OEM solution, will enable the applications of femtosecond phenomena to become a commonly-used technology. Yet only few of the demonstrated fiber lasers are all-fiber and allow direct fiber-end delivery of femtosecond pulses bu the pulse energy is in pJ range and the laser is not PM (see e.g. [1]). Stability of the lasers is yet another issue not often commented upon in the literature. To the best of our knowledge, a stable femtosecond nJ-level monolithic self-starting system with high-PM output characteristics has not been shown so far.

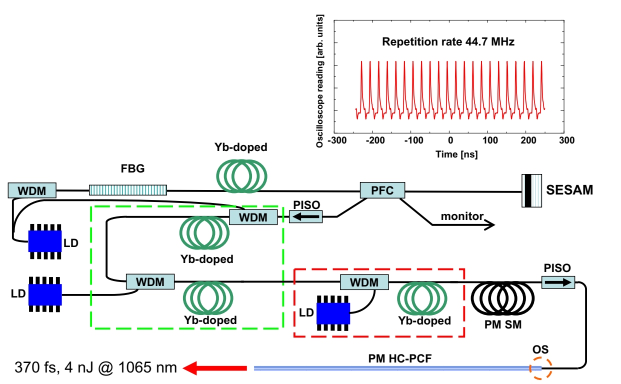

Fig. 1. Laser layout. FBG - fiber Bragg grating, SESAM - semiconductor saturable absorber mirror, WDM - wavelength division multiplexer, PFC - polarization filter coupler, LD - pump laser diode at 976 nm, PISO - polarization-maintaining isolator, PM SM - polarization-maintaining single-mode fiber. PM HC-PCF - polarization-maintaining hollow-core photonic crystal fiber, OS - optimized splice. Inset: oscilloscope reading of the modelocked pulse train.

II. Design, Operation Principles, and Results

The full laser system consists of a modelocked oscillator, a series of pre-amplifiers, a power amplifier, and a spliced-on hollow-core photonic crystal fiber (HC-PCF), in which the output laser pulse is compressed down to femtosecond duration with low loss and a high degree of polarization stability.

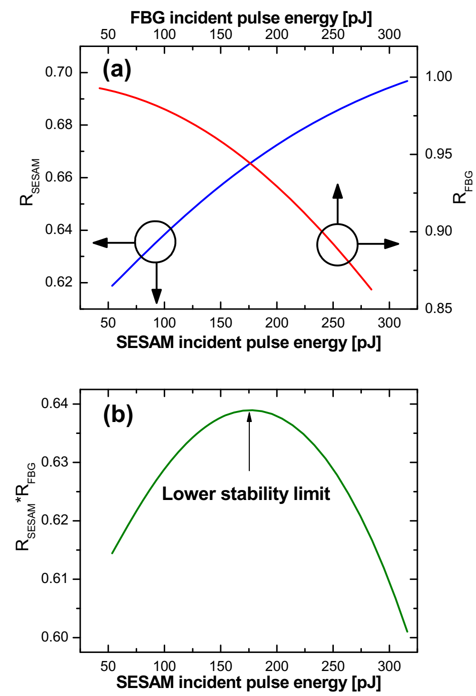

Fig. 2. (a) Reflectivity of SESAM and FBG as a function of the respective incident pulse energy. (b) Combined reflectivity of SESAM and FBG as a function of the energy of the pulse incident on SESAM.

The oscillator involves a linear cavity consisting of polarization-maintaining single mode (PM SM) passive and Yb-doped fibers, confined between a SESAM and FBG, as shown in Fig. 1.

SESAM supports the intensity fluctuations in the cavity, thus providing favorable conditions for self-starting modelocking. On the other hand, due to its nature, SESAM performance may lead to a chaotic Q-switched modelocking regime, where, as a result of a strong spontaneous pulse-to-pulse intensity fluctuation within the modelocked pulse train, the inversion in an active fiber will be fully depleted already by a few laser pulses. Therefore, the laser signal will be chaotically time-modulated by the depletion-recovery dynamics of the inversion in active fiber, resulting in some pulses having giant amplitudes. This regime leads to quick degradation of

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the intracavity components of the oscillator, as well as to a permanent damage to the subsequent amplifier stages.

In order to stabilize our laser against Q-switchng, we employ a narrow-band fiber Bragg grating serving as an end mirror on one side of the cavity. Stronger pulses in optical fibers undergo stronger self-phase modulation, which leads to an increase in the spectral bandwidth of the pulse. Thus, the excess energy of the pulse will be spectrally redistributed to the shorter and longer wavelength sides of the pulse spectrum with respect to its central wavelength. Most of this excess energy, added to a pulse due to a strong intensity fluctuation, will leave the cavity past the narrow-band FBG, and the laser will be stabilized [2]. Therefore, the FBG in this case acts as an optical limiter. The separate and combined contributions of the SESAM and FBG to the total cavity loss are shown in Fig. 2. The laser enters a stable modelocking regime, when the maximum of the combined SESAM-FBG reflectivity is achieved, and the cavity has a minimal loss. The FBG also acts a means of cavity dispersion management in our laser, since the spectrum of any FBG contains the positively and negatively chirping regions. In our laser the pulse is formed on the negatively chirping side of FBG reflectivity spectrum, and thus the effect of propagation through the positively chirping fibers of the cavity is being balanced [3].

Our laser is sequentially preamplified in a chain of single-mode amplifiers in order to achieve a high contrast between the laser output and amplified spontaneous emission in Yb, and finally end-amplified in a booster amplifier. The amplified output of the laser is launched into a long piece of a PM SMF, where its spectrum is broadened up to 11 nm of bandwidth, which permits femtosecond operation. The broadband laser output is then isolated and launched into a PM HC-PCF [4] using an optimized splicing procedure [5].

The SEM image of the HC-PCF used, the resulting mode shape of the laser, and measured and calculated autocorrelations (AC) of the laser pulse are presented in Fig. 3. The mode shape is near-perfect Gaussian with an elongated hexagonal pattern visible in the low-intensity part of the image, which is typical for the birefringent hollow-core PCFs [3], [5]. The measured AC could not be fitted with any parameterized function and had a FWHM duration of 615 fs. The comparison with calculated ACs of the Fourier-limited pulse (pulse shape FWHM of 370 fs, AC FWHM of 596 fs), and of the pulse resulting from a numerical propagation through a HC-PCF (pulse shape FWHM of 415 fs, AC FWHM of 729 fs) shows, that the experimental pulse has a FWHM duration very close to that of the Fourier-limited pulse, i.e. 370 fs. The longer duration of the pulse from HC-PCF propagation model can be explained by sightly lower than specified [4] 3rd order dispersion in the fiber used in our experiment. Combined loss of the HC-PCF compressor, comprising of the splice loss and the attenuation in the fiber, only amounted to 1.35 dB, and the resulting femtosecond pulse energy was 4 nJ.

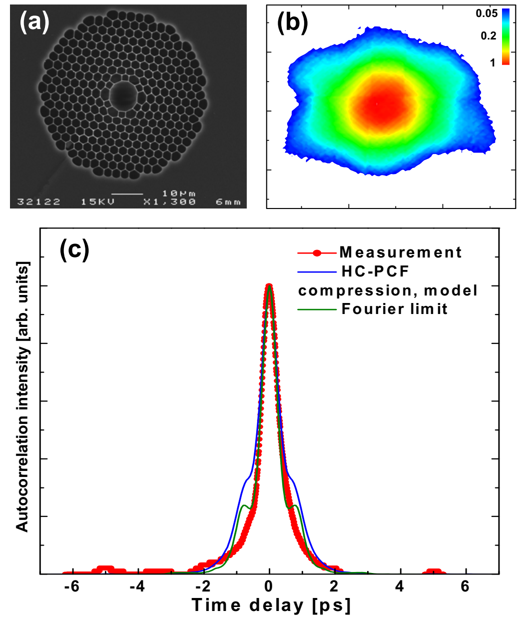

Fig. 3. (a) SEM image of the HC-PCF. Courtesy of B.J. Mangan, Crystal Fibre A/S. (b) Measured far-field mode profile mode on the logarithmic intensity scale. (c) Measured (red) and calculated autocorrelations of Fourier-limited laser pulse (green), and the shortest pulse resulting from the HC-PCF compression modelling (blue).

III. Conclusion

We have presented a fully monolithic (i.e. without any free-space coupling) FBG-stabilized, all-PM femtosecond Yb-fiber laser highly stable against chaotic Q-switched modelocking. Compression of an amplified laser output in the spliced-on PM HC-PCF provides near-transform-limited pulses of around 370 fs duration and 4 nJ pulse energy, directly delivered from the fiber end with a high optical mode quality. Exceptional environmental stability of our laser suggests that it may used as a compact and reliable seed source for the high power applications.

Acknowledgment

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