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# Sub-100 fs pulses from an all-polarization maintaining Yb-fiber oscillator with an anomalous dispersion higher-order-mode fiber

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**Abstract:** We present an Yb-fiber oscillator with an all-polarization-maintaining cavity with a higher-order-mode fiber for dispersion compensation. The polarization maintaining higher order mode fiber introduces not only negative second order dispersion but also negative third order dispersion in the cavity, in contrast to dispersion compensation schemes used in previous demonstrations of all-polarization maintaining Yb-fiber oscillators. The performance of the saturable absorber mirror modelocked oscillator, that employs a free space scheme for coupling onto the saturable absorber mirror and output coupling, was investigated for different settings of the intracavity dispersion. When the cavity is operated with close to zero net dispersion, highly stable 0.5-nJ pulses externally compressed to sub-100-fs are generated. These are to our knowledge the shortest pulses generated from an all-polarization-maintaining Yb-fiber oscillator. The spectral phase of the output pulses is well behaved and can be compensated such that wing-free Fourier transform limited pulses can be obtained. Further reduction of the net intracavity third order dispersion will allow generating broader output spectra and consequently shorter pulses, without sacrificing pulse fidelity.

**OCIS codes:** (060.2320) Fiber optics amplifiers and oscillators; (320.7090) Ultrafast lasers.

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## 1. Introduction

Femtosecond Yb-doped fiber lasers are very attractive sources for ultrafast optical applications because they are intrinsically associated with reduced sensitivity to alignment, compact design and low production costs. Nevertheless, the adoption of these lasers beyond laboratory environments is hindered because of the sensitivity of modelocking operation against external perturbations. In non-polarization maintaining (non-PM) fibers, temperature changes, fiber bending and other mechanical perturbations, can influence the birefringence properties of the fibers which can result in degradation of device performance and eventually losing of modelocking. High pulse fidelity from the oscillator, i.e. pulses compressible to almost Fourier transform limited duration with minimal side structure (which is also reflected by smooth output spectra with a well-behaved spectral phase), is of key importance for many applications, like nonlinear microscopy and seeding of high-fidelity fiber amplifiers. Since environmental instabilities in fiber lasers mainly arise from induced changes in the birefringence of non-PM fibers, the straightforward approach to make the laser robust against them is to use PM fibers with light polarized only along the slow axis [1,2]. A major challenge to develop operational and environmentally stable fiber lasers delivering short-high fidelity femtosecond pulses at 1 μm wavelength is to realize good higher order dispersion compensation [3,4] and to manage intracavity nonlinearities. In non-PM oscillator cavities careful control of the intracavity dispersion has resulted in high quality pulses and the generation of transformed limited wing-free pulses [3,5].

In the last years the development of all-PM fiber sources has attracted much attention, and several –environmentally stable– Yb-doped fiber oscillators based on PM fibers and different approaches for intracavity dispersion compensation and modelocking techniques have been realized. With the aid of a pair of gratings to provide free-space intracavity dispersion [1] a self-similar oscillator with the (linear) cavity comprising only PM single mode fibers (SMF) was demonstrated. Modelocking operation was obtained using a saturable absorber mirror (SAM). Pulse energies up to 1 nJ at a repetition rate of 17 MHz were obtained with the net intracavity dispersion at the oscillator central wavelength ~0.03 $ps^2$. The compressed pulses were evaluated to be ~210 fs. In a different approach, using a PM all-solid photonic bandgap fiber for dispersion management and a SAM for modelocking stabilization, in a linear cavity up to 49 pJ pulses recompressed to a near transform limited duration of around 230 fs [6,7] were generated. The oscillator is reported to operate in a weakly stretched pulse regime with small anomalous cavity dispersion. The net cavity dispersion in one round trip was estimated to be zero at 1024 nm and 0.089 ps/nm at 1033 nm (laser central wavelength). For both of these dispersion compensation approaches, although negative dispersion compensation can be introduced, the anomalous dispersion portion of the cavity introduces additional positive third order dispersion (TOD) instead of compensating the positive TOD of the PM-SMF. It has been shown that the presence of TOD in cavities operating in the stretched pulse mode degrades pulse quality [8]. Therefore a way to minimize the amount of TOD in pulses operating in the stretched pulse regime is highly desirable. Currently, most of the so far realized all-PM oscillator cavities operate in the so-called all-normal dispersion regime. In a realization using spectral filtering along with a SAM to enforce modelocked operation, pulse energies of up to 2 nJ and a duration of 310 fs were realized [9]. The pulses were dechirped using a grating pair to within 10% of the Fourier transform limited duration. The total normal

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cavity dispersion was ~0.17 $ps^2$. In an approach replacing the free-space spectral filtering by a fiber-based solution using tilted-fiber Bragg gratings, 1.36 nJ pulses were obtained [10]. These were compressed down to 457 fs (corresponding to 1.19 times the Fourier transform limited duration). Using a nonlinear amplifying-loop mirror in an all-PM fiber integrated all-normal dispersion cavity, pulses as short as 120 fs with an output energy of 4.3 nJ were generated [11]. The recompressed pulses are substantially longer (55% longer) than the transformed limit duration and a ripple structure on the top of the spectra is also observed. The much longer pulse duration compared to the transform limited duration, is believed to be originated by accumulated nonlinearities and higher-order dispersion effects that are not compensated with the 1200 lines/mm grating compressor. In an attempt to reduce pulse duration without compromising pulse quality, we have previously demonstrated a 61 fs Yb-fiber oscillator in which dispersion compensation was realized with a higher order mode (HOM) fiber [5], but this scheme was based on non-PM fibers with the modelocking mechanism relying on nonlinear polarization evolution and pulse shaping based on spectral filtering. Here, we demonstrate a SAM modelocked all-PM femtosecond fiber laser that uses a recently demonstrated PM-HOM fiber for dispersion compensation [12]. The oscillator delivers ~0.5 nJ pulses as short as 95 fs after external recompression, which represents to our knowledge the shortest pulse duration demonstrated in an all-PM Yb-fiber oscillator. A PM-HOM fiber dispersion compensation scheme offers several desirable features for inclusion in Yb-fiber oscillators. These features include the possibility of introducing spectrally smooth dispersion compensation for higher order dispersion terms, the mode field area of ~40 $\mu m^2$, which is comparable to (even slightly larger) standard PM-SMF. Additionally, integration of solid silica-based HOM fibers is possible using standard fusion splicing techniques.

## 2. Results and discussion

The oscillator cavity is configured as a ring cavity, as depicted in Fig. 1. Non-fiber integrated solutions for light coupling onto the SAM and output coupling are used to allow for ease of optimization of the cavity parameters. It may be noted that fiber-integrated solutions for this are commercially available, allowing for a full-fiber integrated realization of the cavity. Especially for higher output pulse energies (>0.5 nJ, as illustrated below), free-space output coupling has one additional, important, advantage over a fiber-integrated alternative, namely that the fiber-integrated alternative may introduce additional nonlinear phase to the output pulses, which could distort the output pulses. Generally, one may prefer to use a robustly prepared free-space output scheme for high-energy output pulses that can be used for applications without further amplification, and a fiber-integrated output scheme for low-energy pulses that will be further amplified, after sufficient temporal stretching to minimize nonlinearities. Since the purpose of this work is to demonstrate and characterize (in terms of attainable pulse energies, pulse duration and fidelity) the oscillator scheme with PM-HOM fiber, a free space output scheme is preferable.

When adjusting the length of PM-SMF and PM-HOM fiber in the cavity, different operational regimes can be observed. Figure 2(a) shows the dispersion of 1 m of PM-SMF, 1 m of PM-HOM fiber with light propagating in the LP02 mode and of 0.56 m of PM-HOM fiber with light propagating in the LP01 mode (i.e. the total length of PM-HOM fiber before the first and after the second mode converter in the cavity). The net cavity dispersion for different combinations of PM-SMF and PM-HOM fiber lengths are shown in Fig. 2(b). The open symbols correspond to the measured dispersion of the configuration with a repetition rate of 10.46 MHz. The dispersion was measured by introducing a tunable spectral filter in the cavity and recording the roundtrip time as a function of central wavelength of the resulting ps pulses [13]. The TOD extracted from the measured intracavity dispersion agrees well to the TOD corresponding to the dispersion calculated from the measured values of the individual fibers and their respective lengths, while the wavelength at which the dispersion value was zero extracted from the intracavity dispersion measurement (together with the restraint of the measured repetition rate) was used to calibrate the exact lengths of the respective fibers.

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We have measured the pulse duration (after external compression using 800 lines/mm diffraction gratings) using second harmonic frequency resolved optical gating (SH-FROG). At sufficient net normal dispersion (~0.025 $ps^2$ at 1030 nm), the typical rectangular spectral shape observed in net-normal dispersion oscillators is obtained, with stretched output pulses with ~4 ps duration and 0.5 nJ energy, that can be externally compressed to ~190 fs full-width at half-maximum (FWHM) duration (see Fig. 3). The recompressed pulses have a relatively strong pedestal, due to a steep spectral phase at the long-wavelength side of the spectrum. The pedestal can be removed by filtering out this part of the spectrum, resulting in a clean ~190 fs pulse.

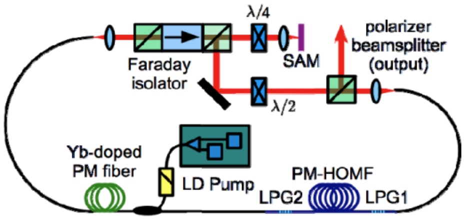

Fig. 1. Schematic of the PM Yb-fiber oscillator. SAM: Saturable absorber mirror (BATOP SAM-1040-40-500fs, spotsize ~5 µm); PM-HOMF: PM higher-order-mode fiber; LPG: Long period grating – LPG1 converts the LP01 mode to the LP02 mode, LPG2 converts the LP02 mode back to the LP01 mode; LD Pump: 600 mW 976 nm laser diode.

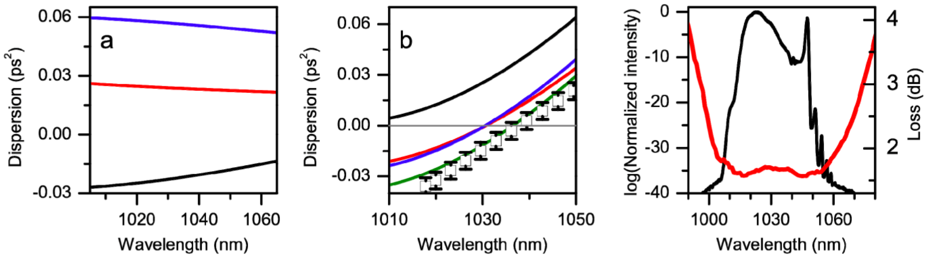

Fig. 2. (a) Dispersion of 1 m PM-SMF (Nufern PM980, red trace), 1m PM-HOM fiber with light propagating in the LP02-mode (black) and 0.56 m of PM-HOM fiber with light propagating in the LP01 mode (blue). (b) Net intracavity dispersion of different oscillator realizations. Black line – 9.8 MHz cavity; blue line – 10.17 MHz cavity; green line – 10.46 MHz cavity; open squares – measured intracavity dispersion of the 10.46 MHz cavity; red line – 11.97 MHz cavity. (c) Logarithmic plot of the spectrum obtained with the net intracavity dispersion close to zero (black) and insertion loss of the PM-HOM fiber module (red).

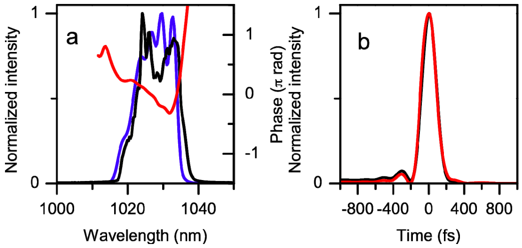

Fig. 3. Output pulses in normal intracavity dispersion regime (9.8 MHz cavity). (a) Spectrum (black – measured, blue – reconstructed) and spectral phase (red) (b) Compressed temporal pulse (FWHM 190 fs) profile, black – full spectrum, red – long wavelength side blocked in compressor.

A reduction of the net normal dispersion (by about 0.01 $ps^2$) brings the oscillator in a regime where only unstable pulsed operation can be obtained, similar to what has been observed in Ti:sapphire oscillators [14]. Even further reduction of the net cavity dispersion (by again about 0.01 $ps^2$) such that it is zero in the range between 1020 nm and 1040 nm results in stable modelocked operation with smooth bell-like spectra, with a small sharp peak on the long-wavelength side. It has to be noted here that this spike is not a cw-spike, but rather the consequence of the (rather large) negative cavity TOD in the vicinity of net zero dispersion, and produces a weak ps pedestal to the pulse (depending on the operation parameters, it may carry up to 5 percent of the total pulse energy, while with careful optimization of the cavity parameters – output coupling ratio, alignment and position of the SAM – it can be minimized, carrying about 0.5 percent of the energy). The maximum obtainable spectral width initially increases with the zero dispersion wavelength shifting to longer wavelengths (i.e. decreasing the net cavity dispersion), and decreases again when the zero dispersion wavelength is shifted beyond 1035 nm (the net cavity dispersion is then anomalous). The spectral width also depends on the output coupling ratio, alignment and focusing conditions onto the SAM, and pump power.

When increasing the pump power from zero, the oscillator self-starts at pump powers below 100 mW, with the same pulse parameters are obtained at each ON/OFF cycle. Increasing the pump power by about 10 percent beyond the threshold for self-starting of modelocked operation increases the spectral width and pulse energy. A further increase by about 10 percent increases the spectral width and pulse energy further, but the increase in intracavity nonlinearities affect the output spectral phase on the pulses leading to an increase of pulse duration after compression with a simple grating compressor. A further increase of pump power leads to multi-pulsed operation. A slow decrease of pump power from the threshold of modelocked operation down to about 80 percent of the threshold is accompanied by a slight decrease of spectral width and pulse energy.

With the cavity parameters optimized to maximize the output bandwidth, and allowing for a small peak on the long wavelength side, at a repetition rate of 10.17 MHz (Net intracavity dispersion at 1030 nm –0.001 $ps^2$) and output pulse energy of 0.5 nJ, 101 fs pulses are obtained after compression with diffraction gratings (~0.5 ps before compression, a small amount of residual TOD after compression is observed, as can be seen in Fig. 4). By compressing the pulses using a combination of gratings, SMF and (non-PM) HOM fiber, essentially Fourier transform limited pulses without residual TOD and 95 fs duration can be obtained, proving that no detrimental nonlinear phase is accumulated that could lead to uncompensable spectral phase. (The spectral width of the pulses is slightly increased, as shown in Fig. 4, which we attribute to a small amount of self phase modulation in the HOM fiber and SMF.) With a further reduction of the intracavity dispersion, which is obtained by decreasing the amount of PM SMF in the cavity (resulting in a repetition rate of 10.46 MHz, and net intracavity dispersion at 1030 nm of –0.012 $ps^2$), the sharp peak on the long wavelength side can be suppressed to a level where it is not detectable, however, as mentioned above, the spectral width of the output pulses is also reduced. Compression of the 0.6 nJ, ~0.5 ps output pulses using a simple grating compressor yields 190 fs pulses, as shown in Fig. 5.

Figure 6 shows the SH-FROG measurement obtained at the optimal cavity parameters for a repetition rate of 11.97 MHz (net intracavity dispersion at 1030 nm is –0.001 $ps^2$), which was obtained by reducing the propagation length in the LP02 mode in the PM-HOM fiber, e.g. shortening the length of PM-HOM fiber between the long-period gratings inscribed at both ends of the PM-HOM fiber, and subsequent reduction of PM-SMF to bring the net cavity dispersion at about 1030 nm to zero. In this case, using only gratings for pulse compression, 97 fs pulses (~0.5 ps before compression) with 0.45 nJ energy were obtained. The pulses are compressed to within 8% of the Fourier transform limit, due to the uncompensated TOD.

The most stable operation of the oscillator is expected to be observed [13] in configurations where the net cavity dispersion crosses zero within the output spectrum. This is confirmed by the RF-spectral measurement presented in Fig. 7. The resolution bandwidth of the spectrum analyzer was 1 Hz, equal to the measured bandwidth of the oscillator repetition rate, indicating a very low timing jitter of the pulse train. The absence of sidebands

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and 80 dB signal-to-background ratio further support this, and additionally show that the pulse-to-pulse energy stability is excellent.

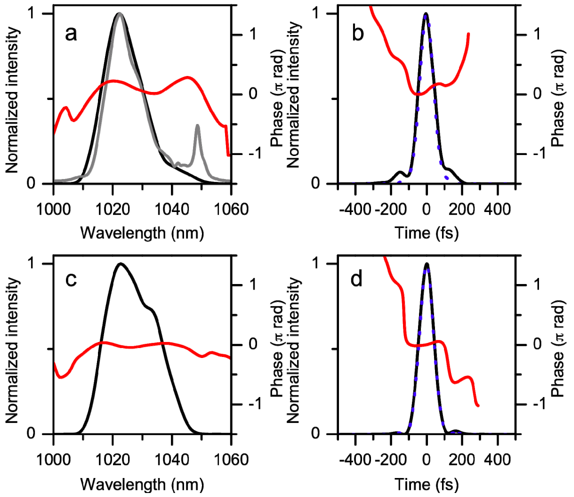

Fig. 4. Output pulses in regime with intracavity dispersion crossing zero within the output spectrum. (10.17 MHz cavity) (a) Spectrum (gray – measured, black – reconstructed) and spectral phase (red) when compressed with a simple grating compressor. (b) Corresponding temporal pulse profile (black, FWHM 101 fs) and phase (red). The dotted blue trace corresponds to the inverse Fourier transform of the retrieved spectrum (FWHM 95 fs). (c) Spectrum (black) and spectral phase (red) when compressed using a combination of SMF, (non-PM) HOM fiber and diffraction gratings, with the lengths set to minimize the TOD on the output pulses. (d) Corresponding temporal pulse profile (black, FWHM 95 fs) and phase (red). The dotted blue trace corresponds to the inverse Fourier transform of the SH-FROG retrieved spectrum (FWHM 94 fs).

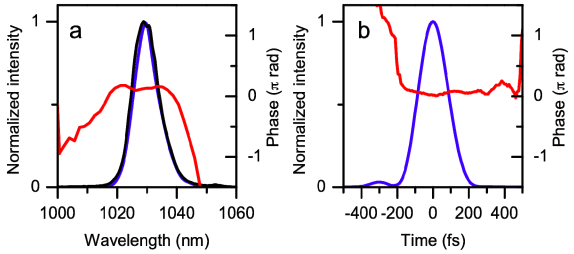

Fig. 5. Output pulses in anomalous dispersion regime. (10.46 MHz cavity) (a) Spectrum (black – measured, blue – reconstructed) and spectral phase (red). (b) Corresponding temporal pulse profile (blue, FWHM 190 fs) and phase (red).

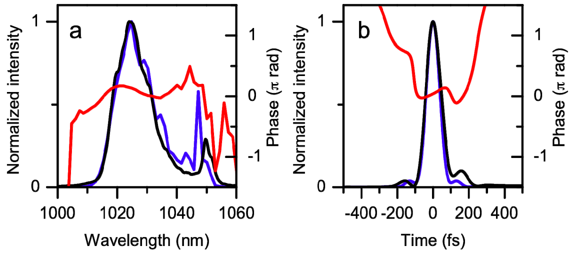

Fig. 6. Output pulses in regime with zero dispersion crossing zero within the output spectrum, with reduced TOD compared to Fig. 4. (11.97 MHz cavity) (a) Spectrum (black – measured, blue – reconstructed) and spectral phase (red). (b) Corresponding temporal pulse profile (black, FHWM 97 fs) and phase (red). The blue trace corresponds to the inverse Fourier transform of the reconstructed spectrum (FWHM 90 fs).

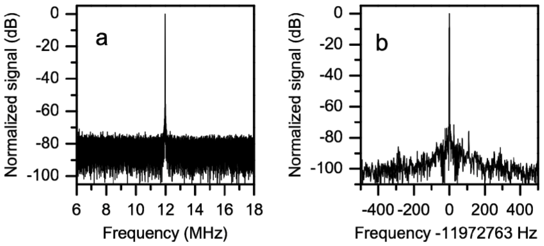

Fig. 7. RF spectrum of the output pulse train. (a) Wide span with 1 kHz resolution bandwidth. The absence of sidebands indicates the pulse-to-pulse energy stability. (b) 1 kHz span around the measured oscillator repetition rate, with 1 Hz resolution bandwidth.

**Table 1. Details of the presented cavity realizations. All realizations include a length of 0.56 m PM HOM fiber with light propagating in the LP01 mode. The net intracavity dispersion value is taken at 1030 nm. Pulse energy was measured before compression. Pulse compression was realized with a grating pair, except * using a grating pair, SMF and (non-PM) HOM fiber.**

| repetition rate (MHz) | net intracavity dispersion (ps$^2$) | length PM SMF (m) | length PM HOM fiber LP02 (m) | compr. pulse duration (fs) | Fourier lim. duration (fs) | pulse energy (nJ) |
|---|---|---|---|---|---|---|
| 9.80 | 0.025 | 9.20 | 10.95 | 190 | 164 | 0.50 |
| 10.17 | -0.001 | 8.10 | 10.95 | 101 | 95 | 0.50 |
| 10.17 | -0.001 | 8.10 | 10.95 | *95 | *94 | 0.50 |
| 10.46 | -0.010 | 7.70 | 10.95 | 190 | 155 | 0.60 |
| 11.97 | -0.001 | 6.75 | 9.55 | 97 | 90 | 0.45 |

In Table 1 we summarize the different oscillator realizations, listing the compressed output pulse duration, energy, intracavity dispersion and respective lengths of SMF and HOM fibers. At each realization the oscillator output energy and pulse properties were measured over several hours of operation and no change was observed, as was also the case in the oscillator we demonstrated in [5]. Also, this new all-PM Yb-fiber oscillator is always self-starting, while in our previous work [5] at the parameter settings required to obtain the shortest compressible output pulses modelocked operation was started through modulation of the output coupling ratio.

## 3. Conclusions

Summarizing, we demonstrated for the first time an all-PM Yb-fiber oscillator that uses a PM-HOM fiber for intracavity dispersion management. We have characterized the output pulses in different operation regimes, and demonstrate that fine control of the intracavity dispersion is key to obtain short, high-fidelity output pulses. With the intracavity dispersion zero at about 1030 nm, the shortest pulses are obtained, with a compressed duration of ~97 fs. This represents to our knowledge the first demonstration of sub-100-fs pulses from an all-PM Yb-fiber oscillator. With a simple grating compressor the pulses can be compressed to almost Fourier transform limited duration, with a small amount of residual TOD.

Further improvements to the pulse duration attainable from the oscillator and the achievable pulse energy can be expected through further optimization of the oscillator cavity dispersion, especially through reduction of the residual intracavity TOD. To a limited extend this can be obtained by minimizing the propagation length in the LP01 mode in the PM-HOM fiber. An optimization of the design of the PM-HOM to better match the higher order dispersion of PM-SMF is possible, which should allow us to obtain broader spectra from an oscillator with practically zero residual intracavity TOD. A completely fiber-integrated version of the cavity can be realized by replacing the free-space focusing onto the SAM by a pigtailed SAM and the free space output coupling scheme by a (fixed or variable) fiber coupler.

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