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Environmentally-stable all-normal-dispersion femtosecond fiber laser

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Abstract

We demonstrate a mode-locked all-normal-dispersion ytterbium-doped fiber laser constructed with polarization-maintaining fibers. Spectral filtering of a chirped pulse in the cavity, along with a semiconductor saturable absorber, produce self-starting femtosecond mode-locked operation with large normal dispersion. Environmentally-stable generation of 2 nJ and 300-fs pulses is achieved.

Femtosecond fiber lasers are attractive short-pulse sources because of their stability, high efficiency, low sensitivity to alignment, compact design and low production cost. There were notable achievements of the pulse energy and the pulse duration in high-energy ytterbium (Yb)-doped fiber lasers recently. Even though several fiber lasers are successful commercially, wide adoption of fiber lasers beyond the laboratory environment is discouraged because the mode-locked operation can be disrupted by external perturbations. Thermal and mechanical perturbations to the fiber can induce random birefringence, which can substantially alter the laser performance.

Ideally, linearly-polarized light along the slow axis of a polarization-maintaining (PM) fiber is robust against such perturbations. Researchers have devoted substantial efforts to development of environmentally-stable mode-locked fiber lasers, in many configurations. Although PM fibers were successfully employed in a variety of laser configurations, building femtosecond Yb-doped PM fiber lasers was challenging. Fiber lasers typically contain an intracavity anomalous group velocity dispersion (GVD) segment, which has been considered a prerequisite to the generation of femtosecond pulses. For Yb-doped fiber lasers, components that introduce anomalous GVD (grating pairs, photonic crystal fibers (PCF), fiber Bragg gratings, higher-order-mode (HOM) fibers, etc.) tend to introduce complications and/or increase cost. The nonlinear polarization evolution (NPE) mode-locking technique, which exploits the cross phase modulation between two polarization modes, is not conveniently applicable to PM fibers.

Various mode-locking mechanisms and means of introducing anomalous GVD into PM Yb-doped fiber lasers have been proposed. A sigma-type cavity utilizing an anomalous dispersion photonic bandgap fiber as a PM fiber was demonstrated [1]. Nielsen *et al.* reported a femtosecond PM linear fiber laser with a semiconductor saturable absorber mirror (SESAM) and a grating pair [2], and a fiber Bragg grating can replace the bulk grating pair [3]. A clever way to implement NPE in a PM fiber laser was also demonstrated [4]: a linear cavity with a Faraday mirror was successfully mode-locked utilizing NPE in the PM fiber. This work established the possibility of NPE in the PM fiber, but the pulse duration was in the picosecond range.

Recently, a femtosecond fiber laser without an intracavity anomalous GVD segment was demonstrated [5]. Self-amplitude modulation in such an all-normal-dispersion (ANDi) laser occurs through spectral filtering of a chirped pulse. A simple environmentally-stable femtosecond fiber laser is anticipated by replacing all fiber components with PM versions and adding a suitable saturable absorber (SA), such as a SESAM. The self-amplitude modulation is dominated by the contribution of the filtering in ANDi lasers, but a significant contribution from NPE has also been required for stable operation. Thus, it is not clear *a priori* that a SESAM will be adequate to stabilize pulses formed by the spectral filtering mechanism. Ortaç *et al.* reported a laser based on single-polarization large-mode-area (LMA) PCF and a SESAM, which generated 750-fs pulses with 25 nJ energy [6]. Pulse shaping in this laser is attributed to saturable absorption, with minimal effects from spectral filtering. The LMA fiber offers intriguing potential for high pulse energies. However, the single polarization operation is sensitive to the exact bending and the orientation of the fiber. Hence, lasers with LMA fibers lose the advantage of the flexible optical fiber. Therefore the laser integration remains complicated and expensive. With free-space pumping, inflexible gain fiber and the laser cavity largely defined by bulk optics, birefringence of the fiber is not likely to be the primary limit to stability of this kind of laser.

In this paper, we report an environmentally-stable ANDi laser. The design is a linear cavity with PM fiber and very large normal GVD ($\sim 0.17 \text{ ps}^2$). The pulse-shaping is dominated by the spectral-filtering mechanism, and self-starting operation is ensured by the inclusion of a SESAM. Strong spectral filtering can enhance the mode-locked spectrum and hence the dechirped pulse duration [7]. Even with such large GVD, the laser generates 300-fs pulses.

A numerical simulation with realistic parameters was performed to understand the detailed operation of a linear ANDi fiber laser. Fig. 1 shows the cavity schematic with numerically simulated spectra at various locations. A Fabry-Perot cavity is chosen since it is the simplest cavity to implement a reflective SESAM. The SA is assumed to saturate monotonically, and to have an infinitely fast response. The fiber section consists of 1 m of single-mode fiber (SMF) followed by 60 cm of Yb-doped gain fiber and another 40 cm of SMF. After the fiber segment, is a Gaussian filter with 12 nm bandwidth (BW). Unlike other normal dispersion fiber lasers which only use the gain spectral filtering effect [6,8], this laser's spectral filtering is dominantly due to the narrow birefringence filter. The pulse traverses the filter twice in each round trip. The output is coupled out with 70% coupling ratio right after the pulse passes the spectral filter in the forward direction, as shown in Fig. 1. Pulse evolution in each segment was solved numerically using a split-step Fourier method until it reaches a steady state [7].

After reflection from the SESAM, the spectrum exhibits a parabolic top, with steep edges (Fig. 1(a)). Weak spectral broadening occurs in the first segment of SMF (Fig. 1(b),(c)). The amplified pulse undergoes substantial self-phase modulation in the following SMF segment, and the spectrum develops sharp peaks near its edges (Fig. 1(d)). These peaks are diminished by the two passes through the filter (Fig. 1(e and f)), and the spectrum mimics the filter characteristic. The spectrum gently broadens on propagation in the backward direction (Fig. 1(g),(h),(i)), and the SA restores the spectrum to that in Fig. 1(a). The self-amplitude modulation is predominantly ($\sim 80\%$ of the total) from the spectral filtering, similar to what was found in ring cavities [5,9]. The simulated main output pulse has 2 nJ energy with ~ 5 ps duration.

The experimental setup is shown in Fig. 2. The SESAM (from BATOP GmbH) has $\sim 35\%$ modulation depth, ~ 40 nm spectral bandwidth (BW) and a relaxation time constant ~ 500 fs. The fiber segments are as in the numerical simulations described above. All PM fiber components were carefully spliced with an estimated extinction ratio over 35 dB. PBS 1, the

birefringent plate, and PBS 2 constitute a birefringent filter with ~ 12 nm BW. The round-trip cavity dispersion is ~ 0.17 ps². The experimental setup is designed to allow maximum flexibility in studies of pulse formation, which is provided by the bulk optics. However, the cavity could be simplified and integrated by replacing all components with fiber-format versions, which are commercially available. Replacing all components with fiber-format versions may change the cavity GVD and the nonlinearity but by selecting the appropriate spectral filter, the desired modes can be obtained [7]. The ejection from the PBS1 (output 1), was monitored to observe the spectrum right after the fiber segment. The reflection from the birefringent plate (output 2) allows us to monitor any modulation on the spectrum transmitted through PBS 1. The double pass through the quarter-waveplate (QWP) rotates the polarization to adjust the coupling ratio of output 3, from PBS 2. Output 3 is the main laser output. Two other outputs from the laser are energy ejected by the filtering action. Energy ejected at the birefringent filter is not useful for most applications due to the low pulse quality. The mode-locked spectra indicates some residual energy in the fast polarization axis of the PM fiber.

If the polarization coupling into the PM fiber or the splicing between PM components is not perfect, some ripples on the top of the spectrum can be observed [2]. Such ripples indicate degradation of the pulse temporal profile or the existence of secondary pulses. PBS 1 can relieve the problem by ejecting residual pulses in the wrong polarization axis of the PM fiber. It also ensures that a linear polarization matching the slow axis of the PM fiber goes back into the fiber segment.

By carefully adjusting the waveplates, a clean mode-locked spectrum without fringes can be obtained at the main output. The SESAM and the spectral filter were both essential for mode-locking. Although only PM fiber components were used, some residual NPE action due to energy in the wrong polarization axis might contribute to mode-locking. However, without a SESAM, stable mode-locked operation did not occur for any orientation of the waveplates. This indicates that the NPE action alone was not strong enough to start the laser.

The output pulse train was monitored with a detector with 300 ps response time, and the autocorrelation (AC) was monitored for delays up to ~ 100 ps. Fig. 3 shows the output. The spectrum from output 1 (Fig. 3(c)) has sharp peaks near its edges, as predicted by the numerical simulations. Spectral fringes with ~ 0.7 -nm spacing indicate possible remote pulses located ~ 5 ps from the main pulse, which roughly matches the polarization mode group delay due to the total linear birefringence. However, the spectrum transmitted by PBS 1 (Fig. 3(d)) is much smoother. It is believed that PBS 1 ejects the energy in the wrong polarization axis of the PM fiber. Even though the transmitted spectrum is less structured, the overall shape does not vary much from the spectrum ejected by PBS 1. The SA modulates the amplitude of the chirped pulse, which in turn produces spectral modulation. The similar spectra transmitted and ejected by PBS 1 also indicate that the NPE only makes a weak contribution to the overall amplitude modulation.

The main output (output 3) spectrum (Fig. 3(a)) has lower peaks due to the spectral filtering. The average power of output 3 was ~ 74 mW (300 mW pump power) with 33 MHz repetition rate, which corresponds to ~ 2.2 nJ pulse energy. The coupling ratio was $\sim 80\%$. The pulse duration was ~ 6 ps (Fig. 3(b) inset) which was dechirped by a grating pair to 310 fs (Fig. 3(b)), which is within 10% of the Fourier-transform limit. The spectral shape, spectral BW, pulse energy, and pulse duration reasonably match the numerical simulation results not only qualitatively but also quantitatively. The operation was unvaried due to external mechanical perturbations to the fiber. The mode-locked operation was unchanged and sustained for ~ 3 days until intentionally interrupted. Improvement of the laser performance by optimization of the parameters is anticipated. Currently, the pulse energy is limited by the available pump

power. However, the numerical simulation indicates that the pulse energy can be improved by 50% by simply increasing the pump power. Multi-pulsing will limit the pulse energy eventually. However, a refined design should be able to go to higher pulse energies. Previously-reported ring cavity ANDi lasers with NPE could operate in a wide variety of modes [7,9]. In contrast, only limited modes are observed with the PM cavity, all similar to that of Fig. 3. It is not understood what restricts the lasing modes in the PM cavity.

To summarize, we demonstrate an environmentally mode-locked femtosecond ANDi fiber laser with a linear cavity design comprising only PM fibers. Experimental results agree well with the numerical simulations. Filtering of a chirped pulse, along with the saturable absorption of a SESAM combine to generate stable, self-starting mode-locked femtosecond pulses at very large GVD.

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Fig. 1. Linear ANDi fiber laser simulation setup with simulated spectra at various locations: SA: saturable absorber; SF: spectral filter; HR: high reflection mirror; SMF: single mode fiber.

Fig. 3.

Output of the environmentally-stable linear ANDi laser (a) output 3 spectrum (74 mW), (b) output 3 dechirped autocorrelation (~ 310 fs) (inset: chirped autocorrelation), (c) output 1 spectrum (3.6 mW), (d) output 2 spectrum (4 mW).