GAUSSIAN SPECTRUM FIBER LASER PULSES GENERATED IN AN ALL-NORMAL-DISPERSION CAVITY *

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Abstract

In this paper, we report on generating a broad bandwidth Gaussian shaped spectrum fiber laser pulse directly in an all-normal dispersive cavity. Pulse-shaping is based on spectral filtering. The spectrum has a ~20 nm 20-dB spectrum bandwidth and is different from the typical spectrum, of steep edge and two spikes. The Gaussian spectrum is preferred since it can be dechirped to a transform-limited pulsed duration. The pulse duration corresponding to this kind of spectrum is ~315fs, and the pulse energy is up to ~9nJ, with a repetition rate of 18.9MHz.

INTRODUCTION

Compared to solid-state lasers passively mode-locked fiber lasers offer a lot of advantages, such as compactness and freedom from misalignment or having a diffraction-limited beam. The use of nonlinear polarization evolution (NPE)[1] as the mode-locking mechanism is very attractive because of its simplicity. Basically, this technique works as follows. The NPE, which is induced by the optical Kerr effect along the fiber and associated with an intra-cavity polarizer, acts like a fast saturable absorber that ensures passive mode-locking (PML).

The need to compensate for positive group-velocity dispersion (GVD) is crucial in femtosecond pulse generation. For an all-fiber configuration, standard optical fibers that provide anomalous dispersion to compensate for the normal dispersion of the gain fiber are available in the 1550nm wavelength region [2] but not in the 1060nm wavelength region. Photonic crystal fiber [3], prisms [4], diffraction gratings [5] and chirped mirrors [6] have all been used for dispersion management in the 1060nm wavelength region. With the dispersion management, the net cavity dispersion can be normal or anomalous. With large anomalous GVD, a soliton pulse (hyperbolic-secant) [2] is produced, with energy restricted to ~0.1 nJ by the soliton area theorem. As the cavity GVD approaches zero, a stretched-pulse (Gaussian) [7] can be produced, which has the broadest spectrum, corresponding to the minimum pulse duration. However, its pulse energy is limited to 1 nJ without pulse-breaking. When the cavity GVD becomes largely normal, a highly-chirped self-similar pulse (parabolic) [8] can be generated.

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However, to simplify the construction and for user's convenience, as well as to exploit the misalignment-freedom and compactness of the all-fiber configuration, it is desirable to construct a fiber laser without any dispersion compensation. Andy Chong et al were first to demonstrate that a mode-locked ytterbium (Yb)-doped fiber laser works in all normal-dispersion regions without intra-cavity dispersion management, and its pulse-shaping mechanism is based on spectral filtering of a highly-chirped pulse in the cavity [9]. This finding has opened a new field in the pulsed laser regime---dissipative solitons, with several, even tens of nJ of pulse energy without wave-breaking. A train of ~1.4ps chirped pulses, spectra with two spikes have been generated directly from the NPE ejection port by Andy Chong et al [9]. In 2012, Hongyu Yang et al reported a 1030 nm-wavelength Yb:fiber laser that produces the shortest/direct output pulse duration (502fs) among all-normal-dispersion fiber lasers. In this report, we exploit dissipative soliton generation [10]. A 315fs fiber laser pulse train has been directly generated in an all-normal dispersive cavity from the NPE ejection port. The spectrum has a Gaussian shape, which is different from the typical spectrum of steep edge and two spikes. The Gaussian spectrum is preferred since it can be dechirped to a transform-limited pulsed duration. The pulse energy is ~9nJ, with a repetition rate of 18.9MHz.

EXPERIMENTAL SETUP AND RESULTS

Figure 1 shows the experimental setup for a Yb-doped all-normal dispersion cavity. The fiber section consists of ~ 6m of SMF and ~1.0m of highly-doped Yb gain fiber, followed by another ~1.5 m of SMF, with a ~1.3m free space distance, and gain fiber with a double-cladding 6- μ m core diameter (which is the same as the 6- μ m core of SMF to decrease the splicing loss). One pump signal combiner (PSC) combines the multimode high power LD (3W) with the gain fiber. The other pump signal combiner is used to combine the Yb-doped fiber with the SMF. NPE is implemented with quarter-waveplates, a half-waveplate and a polarizing beam splitter. An isolator is used to uni-direct the laser. An interference filter centered at 1040 nm, with 12nm FWHM bandwidth, is employed. The filter is placed after the beam splitter. The total cavity dispersion is ~0.196 ps^2. The output of the laser is taken directly from the NPE ejection port.

The threshold pump power for mode-locking is ~2.5W. The output power linearly increases with the pump power

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(see Figure 2). The self-starting mode-locked operation is achieved by adjusting the wave-plates. The laser produces a stable pulse train with an 18.9MHz repetition rate. The maximum output power can reach ~170mW, which corresponds to the pulse energy of ~9nJ. The ratio of pump power to laser power is lower, the main loss occurs in the LD isolator and the two PSCs.

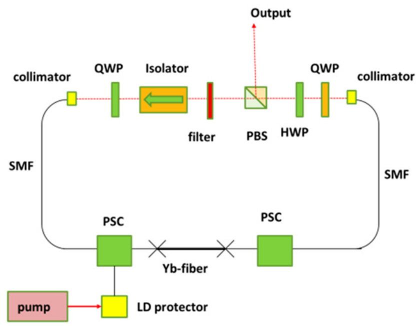

Figure 1: Schematic diagram of the 18.9-MHz all-normal-dispersion Yb-doped fiber laser, PSC: Pump signal combiner, PBS: polarizing beam splitter, SMF: single mode fiber, Yb-fiber: Yb-doped fiber, HWP: half-waveplate, QWP: quarter-waveplate.

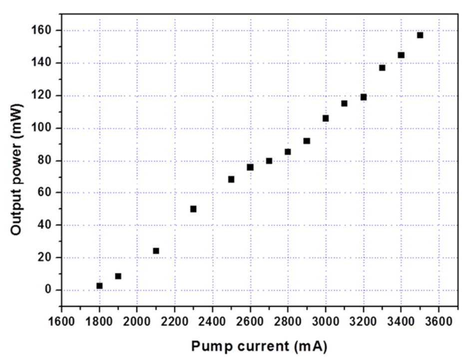

Figure 2: The output power linearly increased with the pump power.

Typical results for the output of the laser are shown in Figure 3. The oscilloscope record of the pulse train (Figure 3 (a)) shows the repetition rate to be 18.9MHz. The pulses are very clear, with no CW background, or side-bands. A typical stable mode-locked spectrum (Figure 3(b), having a Gaussian shape, covers from 1028nm to 1055nm, with a 19.5nm 20dB bandwidth. Intensity auto-correlation, with a Guassian fitting, shows the pulse duration is as short as sub-315 fs (Figure3(c)). According to the spectrum and pulse duration, the time-bandwidth-product of the pulse is ~2.16, which is 5 times higher than 0.441 for Transform limited Gaussian pulses. This high chirping corresponds to the pulse chirped in normal-dispersion SMF. Spectra are carefully monitored for different pump currents. In the case that pump current is increased to achieve mode-locking, when the pump current is lower than the mode-locking threshold current, no stable mode-locking can be produced. However, in the case that pump current is decreased from the mode-locked status, due to the hysteresis phenomenon, when the pump current as low as 2750mA, stable mode-locking can be also maintained. As the pump currents exceed the mode-locking threshold current, centre wavelengths increase and 10dB bandwidths decrease slightly, with the increase of pump currents (see Figure 3 (d)).

The output pulse energy can be tuned from 65mW to 170mW by rotating the wave-plates and adjusting the pump current. The laser is stable and self-starting. Pulse shaping is achieved by the spectral filtering. The spectral filter produces self-amplitude modulation to stabilize mode-locked operation. The behaviour of the laser depends critically on the spectral filter. Without it, a stable pulse train cannot be generated. Also, if the filter's bandwidth is too small, mode-locking cannot be achieved.

The pulse-shaping mechanism of the dissipative soliton is such that: the strong spectral filtering effect of the phase-modulated pulse, produced by the filter provides substantial amplitude modulation [9]. And with the additional amplitude modulation from the NPE, a stable mode-locked region exists. High-energy pulses can be generated in all-normal-dispersion cavities, without pulse-breaking, owing to the self-phase-modulation (SPM) getting stronger with the increase of pulse intensity and nonlinear phase shift. Theoretically pulse energy is expected to increase rapidly with increasing GVD [8]. Due to the strong pulse shaping by the spectral filter, a dissipative soliton laser, operating at large normal cavity dispersion is possible in the presence of a large nonlinear phase shift, compared to solitons, and stretched-pulses.

Our results are quite different from other group's results [9-11]. The dissipative soliton fiber laser always generated several ps pulses, with a typical spectrum of steep edges and two spikes and coverage of 1020-1040 nm wavelength regions [9]. However in our experiment, we generated a femtosecond pulse duration, with a Gaussian-shaped spectrum and 990-1090 nm wavelength regions. This kind of Gaussian spectrum is much better than the spectrum with two spikes, because the spikes in the spectrum indicate that there are more and more modes in the pulse, and this kind of pulse can't be compressed to the shortest pulse duration. The reason for generating a Gaussian spectrum mainly results from the following two conditions: 1) high pump power should be above the threshold to produce firm nonlinearity; 2) SMF has to be long enough. High pump power and a sufficiently long SMF generate a strong SPM, which broadens the spectrum heavily. Because the NPE output port is located before the filter, the filter can't affect the output spectrum directly. When the circulating lasers pass through the filter, the side-wavelengths of the spectrum are cut off. Then the spectrum-abridged circulating lasers return back to SMF from the free-space, and to the gain fiber. The high pump power and sufficiently long SMF, especially the SMF after the gain fiber, generates a very strong SPM, which heavily broadens the spectrum. If the SMF is not long enough, no mode-locking region can be obtained, even at the maximum pump power 3W, which is the highest available pump power of our LD. SMF length before Yb-fiber is ~4m, ~5m, and ~6m cases have also been tested. In the case of the ~4m, ~5m-long SMF before the gain fiber, there is no mode-locking region with the current LD.

Comparing the spectrum before and after the filter (Figure 3(b) and Figure 4), the spectrum is highly abridged by the filter. And the spectrum directly after the filter has a similar shape as the filter. This proves the filter has clipped the circulation spectrum a lot.

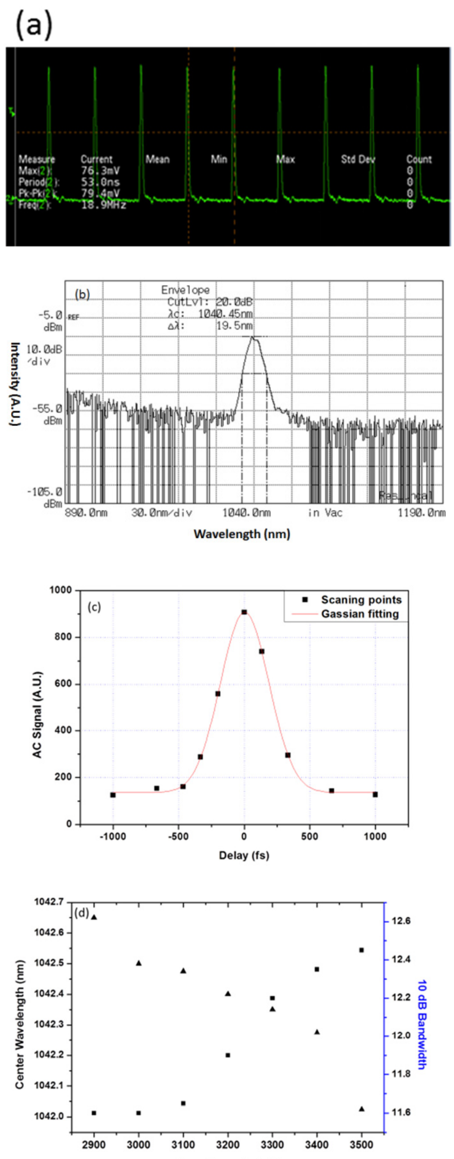

Figure 3: Output of the laser: a) oscilloscope record of the pulse train; b) typical output spectrum and the Gaussian fitting of the stable mode-locked spectrum; c) intensity autocorrelation of the output pulse; d) Stable mode-locked spectra centre wavelengths and 10-dB bandwidths corresponding to pump currents.

To study how the filter abridges the spectrum, we add one PBS after the filter and measure the spectrum of the PBS output, as shown in Figure 4.

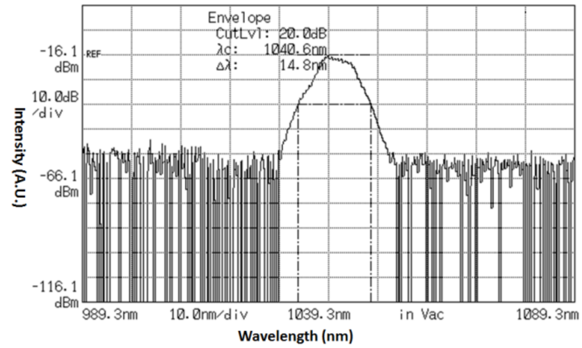

Figure 4: Output laser spectrum directly after the filter.

CONCLUSION

We have demonstrated a fiber laser that generates a femtosecond pulse directly from an all-normal dispersive cavity. The spectrum has a Gaussian shape, with a 20-dB bandwidth ~20nm. The pulse energy is ~9nJ, with a repetition rate of 18.9MHz. We have proved that the strong spectral filtering of pulses in the cavity can provide a pulse-shaping mechanism. The reason why a Gaussian spectrum is generated, but not the typical spectrum of steep edge and two spikes needs to be future studied.

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