SPM-enabled fiber laser source beyond 1.2 µm

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Abstract: Using a home-built, 500-nJ Yb-fiber laser system and large mode area fibers, we demonstrate that SPM-enabled ultrafast fiber source can generate ultrashort pulses with 16.5-nJ pulse energies at 1225 nm.

OCIS codes: (060.4370) Nonlinear optics, fibers; (320.2250) Femtosecond phenomena

1. Introduction

Femtosecond sources operating in 800-1300 nm have received a lot of attention because they are an enabling technology to drive multiphoton microscopy for biomedical imaging [1]. The wavelength range at the longer wavelength side (e.g., 1150-1300 nm) is of particular importance for deep tissue imaging thanks to an optimal combination of low water absorption and reduced light scattering [2]. Meanwhile, less photon energy at longer wavelengths causes less potential photo-damage to the sample. Due to the loss from the microscope optics, femtosecond pulses with >10-nJ pulse energy are usually desired in 1150-1300 nm. The state-of-the-art Cr:forsterite oscillator based on Kerr-lens mode-locking can directly emit femtosecond pulses with 16.5-nJ pulse energy [3]. Unfortunately, limited gain bandwidth of Cr:forsterite crystals makes the emitted pulses in a narrow wavelength range of 1230-1250 nm. Optical parametric oscillators pumped by solid-state lasers can fulfill the requirements on wavelength coverage as well as pulse energy; however, high complexity, high cost, and large size of such a solid-state laser solution have limited the laser system being employed in research labs.

Recently, we demonstrate a self-phase modulation (SPM) enabled ultrafast fiber laser source that can be widely tuned from 825 nm to 1210 nm with >1 nJ pulse energy [4]. SPM inside a short passive fiber broadens an input optical spectrum and generates isolated spectral lobes. We use optical bandpass filters to select the leftmost or rightmost spectral lobes and the resulting pulses are nearly transform-limited with ~100 fs pulse duration. In the previous demonstration, we focus on a broad wavelength coverage using a low-dispersion photonic crystal fiber (PCF) [4]. This PCF exhibits a dispersion of <18 ps/nm/km in 900-1200 nm, which results in a remarkable tuning range of 825-1210 nm for our SPM-enabled source. However, such a low-dispersion PCF possesses a small mode-field diameter (MFD) of only 2.2 µm; the resulting strong nonlinearity limits the pulse energy in 1150-1210 nm to be ~3 nJ. Another paper submitted to this conference by our group demonstrated that using a large mode-area (LMA) fiber with a 7.5-µm MFD can dramatically increase the pulse energy beyond 10 nJ. Limited by available laser power and the zero-dispersion wavelength (ZDW) of the LMA fiber, this energy scaling only succeeds for the wavelength below 1200nm; at 1150 nm, the pulse energy is still less than 10 nJ.

In this submission, we constructed a more powerful Yb-fiber laser system that can produce 30-MHz pulses with >500 nJ pulse energy. This powerful laser source allows us to choose LMA fibers with even larger MFD and longer ZDW for SPM-enabled spectral broadening; the resulting filtered spectrum peaks at 1225 nm corresponding 16.5-nJ pulse energy.

2. Experimental setup and results

Figure 1 illustrates the experimental setup. The home-built high-power fiber laser includes a 30-MHz mode-locked Yb-fiber oscillator centered at 1035 nm, a hybrid fiber stretcher, a single-mode pre-amplifier, a LMA Yb-fiber amplifier, and a pulse compressor. Based on chirped-pulse amplification, this Yb-fiber laser system produces 180-fs pulses with 15-W average power and 500-nJ pulse energy. A half-wave plate together with a polarization beam splitter continuously adjusts the power coupled into a short piece of optical fiber for spectral broadening. At the fiber output, we use an optical bandpass filter to select the rightmost spectral lobe; the resulting pulse train is diagnosed by an optical spectrum analyzer, a power meter, and an auto-correlator. In the experiment, we compare three different commercially available fibers: LMA-PM-10, ESM-12B, and LMA-PM-15; their MFDs are 8.6 µm, 10.3 µm, and 12.6 µm, respectively, at the wavelength of 1064 nm.

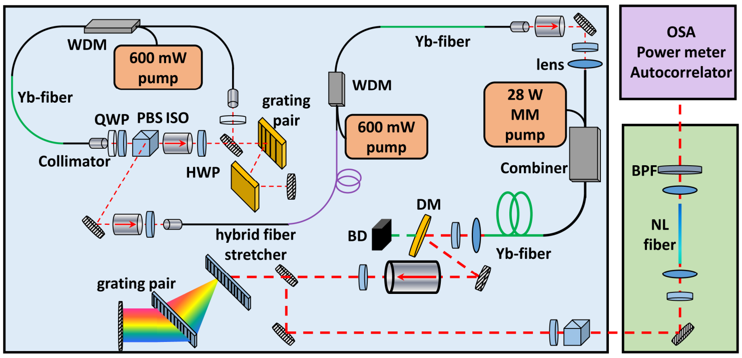

Fig. 1. Schematic setup of SPM-enabled tunable ultrafast source. WDM: wavelength division multiplexer, QWP: quarter wave plate, HWP: half wave plate, PBS: polarization beam splitter, ISO: isolator, DM: dichroic mirror, BD: beam dumper, BPF: bandpass filter, OSA: optical spectrum analyzer.

Figure 2(a) shows the dispersion curves of these three fibers; their ZDWs peak at 1180 nm (LMA-PM-10), 1215 nm (ESM-12B), and 1230 nm (LMA-PM-15). Figure 2(b) shows measured output spectra as we continuously increased the coupled power into 4-cm fiber LMA-PM-10. Clearly with the increased input power, the output optical spectrum becomes broader. The distinct structure of multi spectral lobes indicates that SPM constitutes the main broadening mechanism. At the coupled power of 4.9 W, the entire spectrum (Fig. 2(c)) spans from 920 nm to 1230 nm.

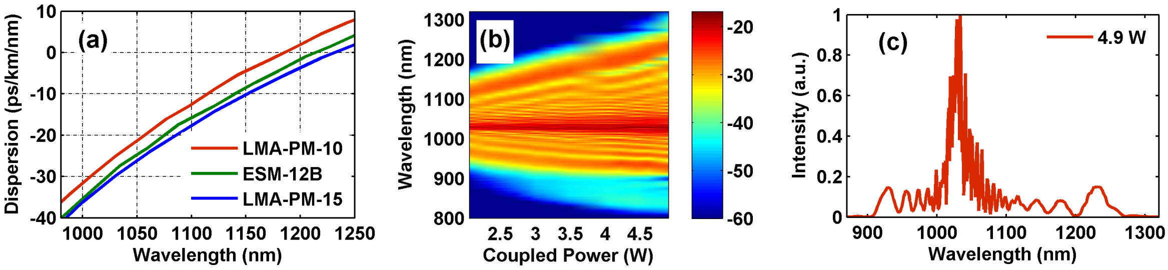

Fig. 2. (a) Dispersion curves of three fibers: LMA-PM-10 (red), ESM-12B (green), and LMA-PM-15 (blue). (b) Measured output spectra versus coupled average power into 4-cm LMA-PM-10. Spectral intensity is shown on a logarithm scale. (c) Output spectrum of 4-cm LMA-PM-10 at coupled power of 4.9 W.

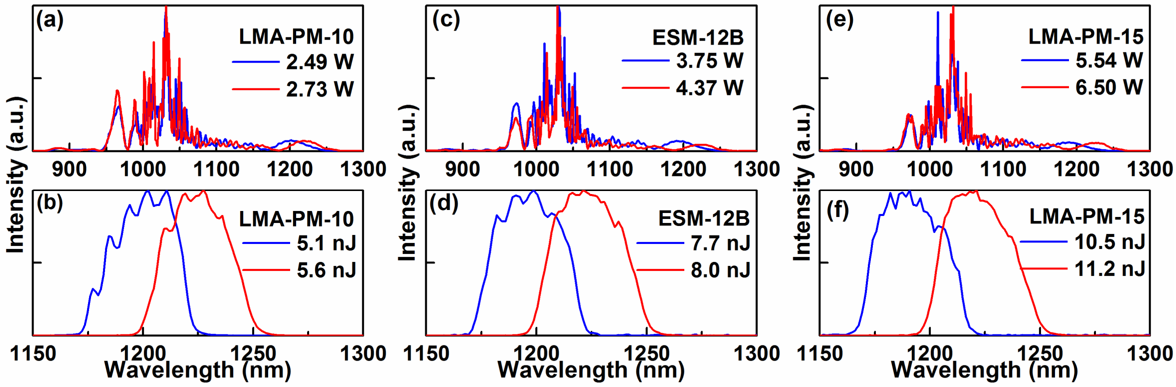

Fig. 3. (a, c, e) Output optical spectra from three different fibers all at 6-cm length: (a) LMA-PM-10, (c) ESM-12B, and (e) LMA-PM-15. We adjust the input pump pulse energy so that the rightmost spectral lobes peak at 1200 nm (blue curve) and 1225 nm (red curve). (b, d, f) filter out spectra from LMA-PM-10 (b), ESM-12B (d), and LMA-PM-15 (f).

To compare the energy scaling performance of these three fibers, all the three fibers are chosen to be 6 cm long. We vary the coupling powers into each fiber such that the rightmost spectral lobe roughly peaks at 1200 nm or 1225 nm. Figure 3 (a, c, e) plot the entire broadened spectra from these three fibers; the coupled average powers are also presented in each figure. Figure 3(b, d, f) record the filtered rightmost spectra and their corresponding pulse energies, which clearly shows that using a fiber with larger MFD results in more pulse energy for the filtered spectrum. More specific, using 6-cm fiber LMA-PM-15, the filtered spectrum that peaks at 1225 nm corresponds to a pulse energy of 11.2 nJ.

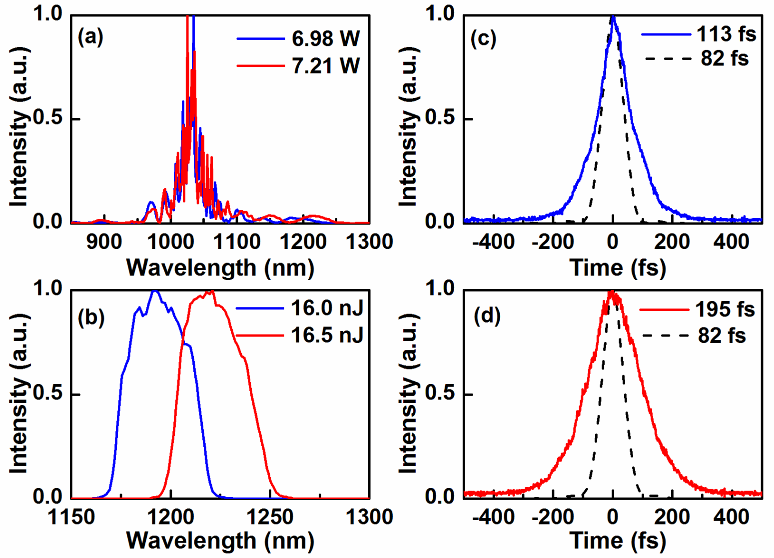

Fig. 4. (a) Output optical spectra from 4-cm LMA-PM-15. (b) filtered spectra peaking at 1190 nm and 1225 nm. (c, d) autocorrelation traces for the filtered spectra. Black dash curves show the calculated autocorrelation traces of the transform-limited pulses allowed by the filtered spectra.

To further scaling the pulse energies, we reduced the length of fiber LMA-PM-15 from 6 cm to 4 cm, a factor of 1.5 times length shortening. More powers were coupled into the 4-cm fiber LMA-PM-15 to achieve the same amount of broadening. Figure 4(a) shows the measured entire spectra with the coupled power at 6.98 W and 7.21 W; their rightmost spectral lobes were filtered and shown in Fig. 4(b). As we expected, the corresponding pulse energy for the filtered spectrum peaking at 1225 nm becomes 16.5 nJ, an approximate 1.5 times more than that obtained from using 6-cm fiber LMA-PM-15. Figure 3(c, d) plot the measured autocorrelation traces for the filtered spectra at 1190 nm and 1225 nm. The black dash curves in these two figures represent the calculated autocorrelation traces of the transform-limited pulses allowed by the filtered spectra. The estimated pulse durations are labeled in Fig. 4 (c, d). For example, the corresponding pulses from the filtered spectrum peaking at 1225 nm have a duration of 195 fs, which can be further compressed to the transform-limited duration using chirped mirrors.

3. Conclusion

We constructed a 500-nJ Yb-fiber laser system to investigate the energy scalability of SPM-enabled ultrafast sources. Using LMA fibers, we show that SPM-enabled spectral broadening followed by spectral filtering can generate ultrashort pulses with 16.5-nJ pulse energies at the wavelength of 1225 nm. Indeed, the source can be further red shifted to the wavelength beyond 1250 nm; however, we are limited by the proper optical bandpass filters to filter these spectral lobes. Ongoing work is to further optimize the system. We believe that >20 nJ femtosecond pulses with the wavelength tunable in the entire 1200-1300 nm range can be achieved.

4. References

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