nJ-class all-PM fiber tunable femtosecond laser from 1800 nm to 2050 nm via a highly efficient SSFS


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ABSTRACT

Nowadays, the request for femtosecond lasers operating between 1.7 µm and 2 µm is continuously growing for many applications. Mode-locked Holmium- or Thulium-doped fiber lasers based on Saturable Absorber Mirror (SAM) are typically the first approach to generate pulses in this spectral range but this technique suffers from a lack of tunability. Indeed, the operating wavelength is fixed by the SAM and the gain fiber. Another way to reach the 2 µm-spectral range consists to exploit the nonlinear phenomena appearing in optical fibers and in particular the Soliton-Self Frequency Shift (SSFS) effect from an Erbium-fiber laser. Several systems based on this phenomenon allowed the generation of ultrashort pulses at different wavelengths and in different type of fibers (step-index, PCF, …).

In this paper, we report on the design of a compact and robust all-Polarization-Maintaining (PM) fiber system entirely based on commercial PM components. This system allows to generate a single femtosecond pulse continuously tunable from 1700 nm to 2050 nm. We also demonstrate that the sub-150 fs pulses are transform-limited over all the spectral range and thanks to an optimized rate conversion close to 50 %, the pulse energy and the peak power can reach the nJ-class and the kW-class respectively, which represents a gain a of factor 2 compared to the previous works.

Keywords: Femtosecond tunable pulses, 2 µm, Soliton Self Frequency Shift

1. INTRODUCTION

Since the last two decades, ultrashort lasers operating around 2 µm have been used for many industrial and scientific applications, such as mid-infrared supercontinuum generation [1-2], micromachining, or like pump of optical parametric oscillators. Usually, lasers are mode-locked cavities based on Holmium- or Thulium-doped fiber associated with SAM. However, the main issue of this kind of laser is the fixed operating wavelength, due to the design of the cavity. To obtain a tunable and robust pulsed fiber laser in the mid-infrared, an alternative approach consists to use an Erbium-doped mode-locked oscillator at 1.5 µm and to exploit the SSFS effect to generate pulses around 2 µm [3-4]. Under the action of the Raman effect, a pulse undergoes a continuous shift towards high wavelengths. Thus, several systems based on this phenomenon with different architectures were already reported [5-8]. More recently, a femtosecond Erbium-doped fiber laser coupled to a Photonic Crystal Fiber (PCF) and a normal dispersion fiber has enabled to generate pulses tunable between 1700 nm and 2100 nm [7]. The low rate conversion (about 20 %) and the use of expensive and custom PCF may be a limitation.

We present here the design of a compact and robust PM all-fiber system able to generate sub-150 fs pulses tunable between 1700 nm and 2050 nm with a conversion rate greater than 50 %. The entire system is only based on commercially PM components.
The experimental setup, shown in the Figure 1, is composed of three main parts: a home-made Erbium-doped fiber mode-locked femtosecond oscillator, an Erbium-doped fiber amplifier and a passive nonlinear fiber.

The mode-locked oscillator delivers 420 fs-long transform-limited pulses at 1560 nm with a pulse energy of 95 pJ at 40 MHz. Pulses are then injected into a short segment of a highly Erbium-doped fiber amplifier, which is bidirectionally pumped by two 976 nm pump diodes. Thanks to the normal dispersion of the fiber, the spectrum is broadened by the self-phase modulation effect [10]. In the time domain, the shape of the amplified pulses tends toward a parabolic shape and is stretched up to 5 ps. At the output of the amplifier stage, pulses have an energy around of 3 nJ, which represents a gain up to 15 dB [cf. Figure 2].

The efficiency of the SSFS effect is studied in two PM silica step-index single-mode fibers (PM1550-XP and PM1950) having a negative dispersion ($\beta_2 < 0$, D > 0) beyond 1550 nm. They are manufactured by Nufern [Nufern] and their optical characteristics are summarized in the Table 1. The fibers have the same dispersion curve but the PM1950 fiber has a nonlinear coefficient greater than the one of the PM1550-XP.

Table 1. Summary of the passive fibers parameters [11-12].

<table>
<thead>
<tr>
<th>Passive fiber</th>
<th>PM1550-XP</th>
<th>PM1950</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiber Name</td>
<td>PM1550-XP</td>
<td>PM1950</td>
</tr>
<tr>
<td>Dispersion</td>
<td>20 ps/(nm.km) @ 1550 nm</td>
<td>35 ps/(nm.km) @ 1950 nm</td>
</tr>
<tr>
<td>Mode-field diameter</td>
<td>10.1 ± 0.4 µm @ 1550 nm</td>
<td>8 µm @ 1950 nm</td>
</tr>
</tbody>
</table>

At the output of the system, pulses are spectrally and temporally characterized thanks to an optical spectrum analyzer and a second-order autocorrelator.

Figure 2. Evolution of the average power (black curve) and the gain (red curve) as a function of the pump power.
3. EXPERIMENTAL RESULTS

Experimental results obtained with the two passive fibers are discussed in the following sections. To evaluate the efficiency of the SSFS effect, we measure the average power with and without a suitable optical filter.

3.1 Nufern PM1550-XP

First, we use 2 m of PM1550-XP as passive fiber. At the output of the entire system, the total output average power around 140 mW. Figure 3(a) shows an example of spectrum where the central wavelength and the spectral bandwidth of the red-shifted pulses are 1744 nm and 40 nm respectively.

After a long-pass filter having a cut-off wavelength at 1600 nm, the average power is 97 mW, corresponding to a rate conversion close to 70 % and energy per pulse up to 2 nJ. In the time domain, the shape of the autocorrelation trace is not modified by the filter. The Full Width at Half Maximum (FWHM) of the autocorrelation trace is 125 fs-long [cf. Figure 3(b)]. If we assume that the temporal shape is a hyperbolic secant, then the pulse duration is 80 fs-long. The shifted pulse thus reaches a peak power of 24 kW and the polarization extinction ratio is around 25 dB.

If we increase the length of the PM1550-XP fiber, we observe that the central wavelength of the red-shifted pulses does not exceed 1800 nm. This observation can be explained by the fact that the losses of the silica fiber are significant at 1800 nm and the decrease of the nonlinear coefficient.

To increase the tunability of our source beyond 1800 nm, we replaced the PM1550-XP fiber by a fiber having a higher non-linear coefficient at the higher wavelength.
3.2 Nufern PM1950

Then, we use 9 m of PM1950. Figure 4(a) shows the evolution of the spectrum as a function of the total average power at the output of the nonlinear fiber. By adjusting the pump powers, our system is able to generate a single pulse finely tunable between 1700 nm and 2050 nm.

![Figure 4. (a) Spectral evolution as a function of the average power at the output of the nonlinear fiber and (b) Evolution of the pulse average power as a function of the pulse central wavelength. In this case, the power is between 28 mW and 53 mW, corresponding to a pulse energy between 0.7 nJ and 1.3 nJ. Furthermore, we observed that more than 50 % of the spectral energy is contained in the red-shifted pulses.]

We use an optical bandpass filter centered at 2000 nm and having a bandwidth of 500 nm to eliminate the unwanted wavelength and measure the power of the red-shifted pulses.

We have then recorded the autocorrelation trace for different pump powers. Figure 5 shows the experimental and numerical traces of the red-shifted pulses at 1800 nm [Figure 5(a)] and 2050 nm [Figure 5(b)]. Note that the numerical autocorrelation trace is calculated from the Fourier transform of the spectrum considering a flat spectral phase. We found that these two traces are similar at 1800 nm whereas this is not really the case at 2050 nm.

![Figure 5. Experimental (black line) and Numerical (red line) autocorrelation traces of the red-shifted pulse when the central wavelength is (a) 1850 nm (b) 2050 nm. (c) Evolution of the FWHM of the autocorrelation trace as a function of the soliton central wavelength. The numerical autocorrelation trace corresponds to the Fourier transform of the spectrum assuming a flat spectral phase.]

Figure 5(c) shows that the gap between experimental and numerical autocorrelation duration increases with the red-shifted pulses central wavelength. We think that this effect is due to the loss bending, responsible of the increase of the experimental autocorrelation width and we note that the polarization extinction ratio cannot exceed 14 dB.

Despite everything, our system is able to generate a sub-150 fs pulse tunable between 1700 nm and 2050 nm with pulse energy up to 1 nJ.
Table 2 summarizes the mainly optical features of the shifted pulses from 1800 nm to 2050 nm.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$\lambda_{\text{min}}$ (nm)</th>
<th>$\lambda_{\text{max}}$ (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central wavelength</td>
<td>1800</td>
<td>2050</td>
</tr>
<tr>
<td>Spectral bandwidth</td>
<td>29.4</td>
<td>33.5</td>
</tr>
<tr>
<td>Pulse average power</td>
<td>28 mW</td>
<td>52.6 mW</td>
</tr>
<tr>
<td>Autocorrelation width</td>
<td>170 fs</td>
<td>208 fs</td>
</tr>
<tr>
<td>Pulse width</td>
<td>113 fs</td>
<td>140 fs</td>
</tr>
<tr>
<td>Pulse peak power</td>
<td>5.46 kW</td>
<td>8.2 kW</td>
</tr>
</tbody>
</table>

To improve the PER value, we realize the same experiment with several segments of fiber.

Figure 6(a) shows the spectrum after 2 m of PM1950 when the output average power is fixed to 117 mW. The central wavelength and the spectral bandwidth of the solitonic pulses are 1970 nm and 44 nm respectively. After the bandpass filter, the average power is around 67 mW, corresponding to a rate conversion closed to 57 % and a pulse energy up to 1.6 nJ. From the Fourier transform of the optical spectrum (and assuming a flat spectral phase), we found that the time-bandwidth product is closed to 0.315. Experimentally, the FWHM of the autocorrelation trace, presented in Figure 6(b), is 131 fs-long. If we assume that the temporal shape is a hyperbolic secant, then the pulse duration is closed to 85 fs. The shifted pulses reach a peak power of 17.3 kW. The PER value is now 24 dB, which represents a gain of 10 dB compared to previous works.

![Figure 6](https://example.com/figure6.png)

Figure 6. (a) Spectrum after 2 m of PM1950 fiber with an average power of 116 mW and (b) Experimental (black line) and numerical (red circles) autocorrelation traces. The numerical autocorrelation trace corresponds to the Fourier transform of the spectrum assuming a flat spectral phase.

![Figure 7](https://example.com/figure7.png)

Figure 7. (a) Spectrum after 1 m of PM1950 fiber with an average power of 117 mW and (b) Experimental without (black line), with (green circles) and numerical (red circles) autocorrelation traces. The numerical autocorrelation trace corresponds to the Fourier transform of the spectrum assuming a flat spectral phase.
Figure 7(a) shows the spectrum after 1 m of PM1950. Spectral fringes are due to the apparition of water vapor in the spectrometer. The pulse duration is 69 fs and the peak power is around of 20 kW [cf. Figure 7(b)]. Our system is always able to generate a red-shifted ultrashort pulse in the mid-infrared.

4. CONCLUSION

In this paper, we reported on a compact and robust all-fiber system generating sub-150 fs pulses tunable from 1700 nm to 2050 nm only made with commercial PM components. Thanks to a rate conversion greater or closed to 50 %, the energy per impulsion and the peak power can reach nJ-class and kW-class respectively, which represents a gain of 3 dB compared to the previous works. To our knowledge, this works presents the first PM fibered laser based on SSFS in the nJ class without use of PCF or HNLF. To increase its scope, this tunable laser could be easily amplified thanks to the wide variety of existing doped fibers or bulk-material in this frequency range.

REFERENCES

[12] Nufern PM1950, Datasheet