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Temporal distribution measurement of the parametric spectral gain in a photonic crystal fiber pumped by a chirped pulse

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Abstract: The temporal distribution of the spectral parametric gain is experimentally investigated when a chirped pump pulse is injected in a photonic crystal fiber. A pump-probe experiment was developed and the important characteristics was measured as the chirp of the pump, the signal pulse and the gain of the parametric amplifier. We highlight that the amplified spectrum depends strongly on the instantaneous pump wavelength and that the temporal evolution of the wavelength at maximum gain is not monotonic. This behavior is significantly different from the case in which the chirped pump has a constant peak power. This measurement will be very important to efficiently include parametric amplifiers in laser systems delivering ultra-short pulses.

Keywords: Parametric amplification; Four wave mixing; Fiber Optics

1. Introduction

Ultra-fast optical parametric amplification (OPA) has already demonstrated many interesting features for the amplification of ultra-short pulses. It allows to get a very high gain value and a very large gain bandwidth to amplify pulses with a duration as short as few optical cycles [1]. In addition, as the parametric process is based on an instantaneous nonlinearity, this type of amplification is of prime interest to maintain or enhance the temporal contrast [2,3]. Most of the OPA based ultra-fast sources are developed with nonlinear crystals as the amplifier media and they are often reliable enough for most of applications [4]. Alternatively, ultra-fast four wave mixing in an optical fiber is a promising direction toward the OPA of ultra-short pulses at high gain in a compact and rugged geometry [5,6]. In this case, the ultra-short signal has a very large bandwidth and is firstly stretched before the amplification to decrease the peak power and to limit spurious nonlinearities in the fiber. After the amplification, the signal is recompressed close to its initial pulse duration. The strong pump pulse has a relatively long duration (tens of ps to ns) to match the one of the stretched signal [5, 7-9]. More recently, several configurations of fiber based OPA have been performed to amplify a very large spectral width at high gain [10-13] or a narrower band at high energy in the µJ range [14-16]. In particular, we have shown that ultra-broad band parametric amplification at high gain can be obtained by using a single pump stretched pulse with a relatively broad spectrum [10-11]. In this

case, the spectral parametric gain is distributed in the temporal domain since the instantaneous frequency of the pump changes quasi-linearly with time due to the chirp rate. Therefore, we can expect to amplify a stretched ultra-short pulse when a broad band signal is simultaneously injected in the optical fiber [12]. However, the instantaneous frequencies of the stretched signal also change with time and they need to match the temporal distribution of the spectral gain. In addition, the temporal shape of the pump impacts strongly the parametric gain shape since the gain value and/or the phase matching condition depend both on the instantaneous power injected in the fiber [16,17] or in a nonlinear crystal [18]. Therefore, it is very important to measure and understand the temporal distribution of this spectral gain in order to design ultra-broad band parametric amplifiers. This feature cannot be measured with a spectrometer that record a time integrated spectrum. Hence, in this manuscript, we present a pump-probe method with stretched pulses to diagnose this distribution. The paper is structured as follow. In Section 2, we present didactic examples to highlight the temporal evolution of the spectral gain when the pump power is not constant during its duration. In Section 3, we describe the experimental set-up. The most important properties was measured as the chirp of the pump, the signal pulse and the parametric fluorescence. The measurement of the parametric gain as a function of the delay between the pump and the probe is discussed in Section 4. We highlight that the amplified spectrum depends strongly on the instantaneous pump wavelength and that the temporal evolution of the wavelength at maximum gain is not monotonic. Finally, we conclude the article in Section 5.

2. Parametric amplification in fiber pumped by a structured and chirped pump pulse

Parametric amplification in fiber of an ultra-short pulse relies on a phase matched four wave mixing of a stretched signal with a very large bandwidth, a strong pump pulse with a power P and a generated idler. In this manuscript, the pump will be a chirped pulse. The gain of the signal is maximum when all the involved waves are phase matched according to

$$\kappa(\Omega,t)=\beta_{20}\cdot\Omega^2+\frac{\beta_{40}}{12}\cdot\Omega^4+2\gamma P(\tau)=0 \quad (1)$$

with β_{20} and β_{40} the second and fourth order dispersion terms at the pump wavelength λ_P. We neglect higher order terms. Ω is the angular frequency offset from the pump. γ is the nonlinear coefficient of the fiber and is set to 35 $W^{-1}.km^{-1}$. In order to calculate the phase matching condition (Eq. 1), we consider the photonic crystal fiber (PCF) used in the experiment. From the input facet of the PCF measured with a scanning electron microscope (inset in Figure 1.a), the second order dispersion term

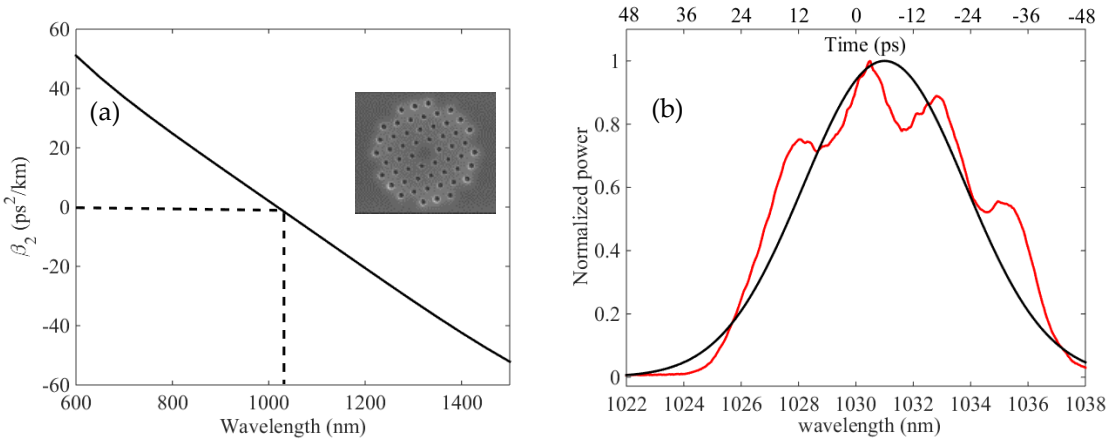

Figure 1. (a) Second order dispersion term as the function of the wavelength. Inset. Input facet of the PCF measured with a scanning electron microscope. (b) Normalized pump spectrum of a chirped pulse with a Gaussian shape (black line) or with the experimental profile (red line).

as the function of the wavelength is calculated (Figure 1.a). The SEM image is first, turned into a two-color image that represents the refractive index map. A mesh is then created from this index map and both, effective indices and intensity distributions of electric and magnetic fields are then calculated using a commercial mode solver based on the finite element method. The chromatic dispersion curve is simply deduced from the effective index one leading to the determination of the zero dispersion wavelength (ZDW) at 1020 nm.

For comparison, we firstly calculated the phase matching condition as a function of λ_p for a constant peak power of 600 W (Figure 2, magenta solid lines) and 200 W (Figure 2, cyan solid lines). In both cases, the phase matched wavelengths evolve monotonically with λ_p. Since we aim to investigate the impact of the pulse shape of a chirped pump, the instantaneous power P will be time dependent in the following. For example, the spectral profile of the pump originated from an ultra-fast laser has usually a Gaussian profile. In our configuration, the pulse is stretched with a linear chirp rate $\alpha=\tau/(\lambda_p-\lambda_{p0})$ with λ_{p0} the pump central wavelength. Therefore, the temporal profile has also a Gaussian profile. Figure 1.b (black line) displays a spectrum centered at λ_{p0}=1031 nm with a bandwidth equals to 6 nm at Full Width at Half Maximum (FWHM). The full pump spectrum lies in the anomalous dispersion regime of the PCF. For α=6 ps/nm close to the experimental value, the pulse duration is 36 ps. Figure 2 shows the phase matching condition calculated from Eq. 1 for the Gaussian pump profile with a maximum power of 600 W (red solid line) and 200 W (blue solid line) at 1030 nm.

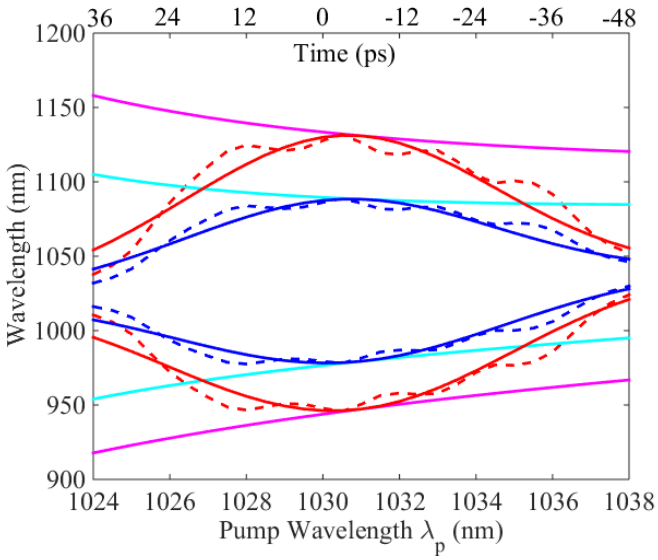

Figure 2. Phase matching as a function of the pump wavelength for a chirped pulse with a Gaussian spectrum (solid red and blue lines) or with the experimental profile (dashed red and blue lines). The maximum power is 600 W (red lines) or 200 W (blue lines). The magenta and cyan lines correspond to the phase matching for a constant peak power of 600 W or 200 W, respectively.

In these cases, the curves are not monotonic and have Bell shapes with a maximum and a minimum at 1131/946 nm (for 600 W) and 1088/978 nm (200 W) at λ_p~1031 nm. As a result, the phase matched wavelength can be obtained at two different λ_p. For example, the parametric amplification at 1100 nm can occur at λ_p~1027 nm and λ_p~1034 nm. For the chirped pump pulse owing a linear temporal distribution of λ_p, it also means that the amplification at 1100 nm can be obtained at two times delayed by 43.4 ps. When a signal is injected in the PCF simultaneously with the chirped pump, its amplification is considerably affected by the pump shape. For a CW signal [15], two delayed amplifications occur and therefore, two idler pulses are generated during the parametric process.

Alternatively, if a chirped seed with a broad bandwidth is injected in the FOPA [12], the parametric process will reshape the amplified signal and it depends strongly on the delay between the signal and the pump. In addition, any variation of the pump profile will modify the phase matching condition. In our experiment, the pump spectrum is modulated (Figure 1.b, red line) impacting also the phase matching condition (Figure 2, dashed lines). It is worth noting that Figure 2 takes into account only the parametric process in the strong pump regime. The saturation and the Raman process are not included although it may modify the amplification behavior. Therefore, it is highly important to directly measure the temporal distribution of the spectral gain in the experimental conditions.

3. Experimental set-up and main parameters

3.1. Pump-probe set-up

The experimental setup is displayed in Figure 3. The pump and the signal are both generated from a unique mode-locked oscillator (Flint, LightConversion) delivering a train of pulses at 76 MHz with a duration of 80 fs at FWHM centered at 1030 nm. The total average power is 1.5 W. The pump wavelength is set at 1030 nm while the signal one should be tunable to seed the targeted parametric amplification band. In order to shift the signal spectrum, a beam splitter selects a part of the oscillator output and 400 mW are injected in an all normal dispersion fiber (ANDI) to generate a coherent continuum [19]. It extends from ~750 nm to 1250 nm and therefore it can be used to seed a parametric amplifier in this band. Then, the continuum is injected in a Öffner type stretcher. The selection of the signal wavelength is achieved by the stretcher alignment by rotating the grating. The spectral bandwidth is imposed by the finite size of the mirrors in the stretcher. The other part of the oscillator (around 750 mW) seeds the pump amplifier. It is composed of a volume Bragg grating (VBG) that stretched the pulses to a duration of few tens of ps. The chirped pulse is then injected in an acoustooptic modulator (AOM) to decrease the repetition rate to 1 MHz and amplified by two ytterbium doped fiber amplifiers (YDFA). The maximum average power is 1 W. Finally, the pump and the signal are both injected in the 5 meter long PCF. The properties of the PCF was described in Section 2. The two pulses are synchronized with a delay stage and the amplification spectrum is measured with an optical spectrum analyzer (OSA) for several delays. As the signal is shorter than the pump pulse, the instantaneous gain is measured for a selected part of the pump.

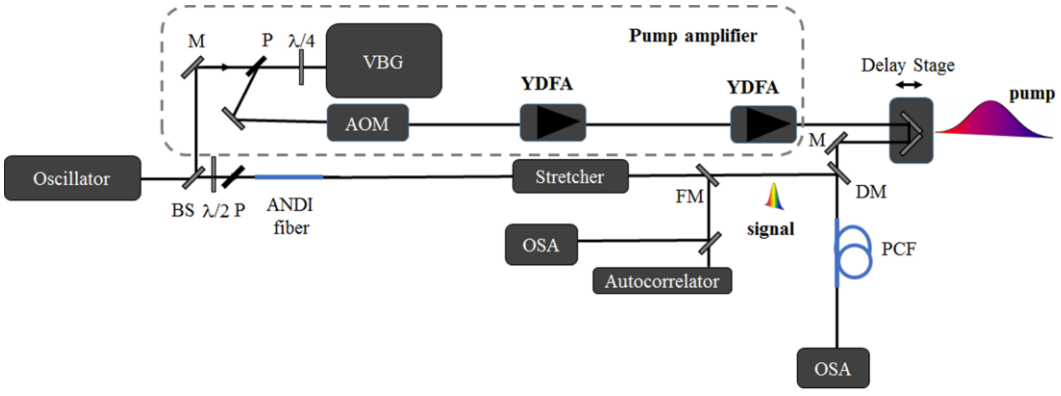

Figure 3. Experimental set-up. VBG, volume Bragg grating; AOM, acoustooptic modulator; YDFA, ytterbium doped fiber amplifier; OSA, optical spectrum analyser; PCF, photonic crystal fiber; ANDI, all normal dispersion fiber; BS, beam splitter; M, mirror; P, polarizer; DM, dichroic mirror; FM, flipped mirror;

The spectrum at the PCF output was firstly measured with the OSA for an average pump power of 31 mW, when the signal was not injected (Figure 4.a). It shows two lobes at 992 nm and 1077 nm

together with the pump spectrum at 1030 nm. The bandwidth at 1077 nm is ~12 nm. The experimental pump spectrum is shown in Figure 1.b (red line) and exhibits structures due to self phase modulation (SPM) occuring in the last YDFA. Therefore, we expect that this spectral modulation will impact the temporal distribution of the spectral gain. In the next section, the signal will be injected in the PCF together with the chirped pump pulse. Therefore, the continuum (black line in Figure. 4.b) is filtered in the stretcher to select the signal spectrum at 1080 nm (red line in Figure. 4.b) close to the central value of the lobes (Figure 4.a). The spectral bandwidth is 15 nm (FWHM). The duration of the stretched pulse was measured with an autocorrelator and the experimental trace is shown in Figure 4.c (red points). From a Gaussian fit (solid black line in Figure 4.c), we deduce a pulse duration of 4.2 ps. This pulse duration is a good compromise since several constraints need to be considered. Indeed, a very short pulse allows to get a high temporal resolution in the pump-probe measurement.

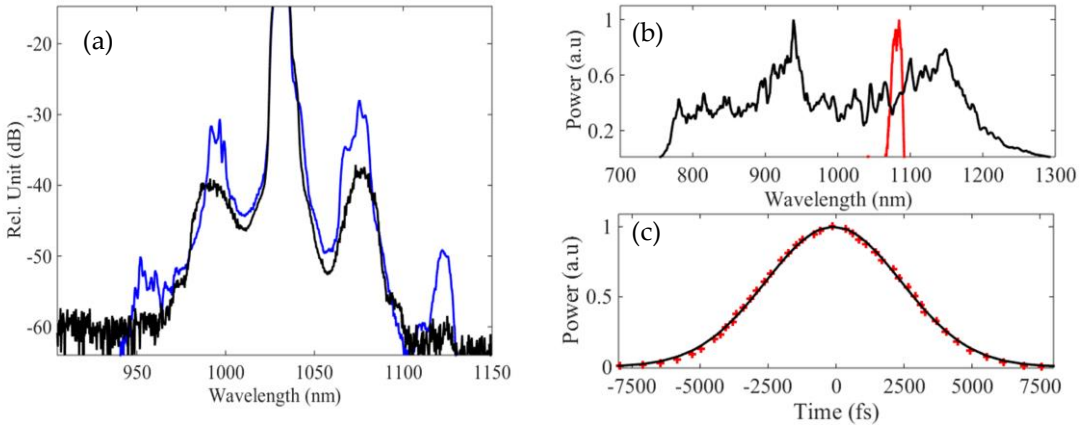

Figure 4. (a) Fluorescence spectrum when the PCF is pumped by 31 mW (black line). Output spectrum when the signal is injected at null delay (blue line). (b) Spectrum of the continuum generated in the ANDI fiber (black line) and spectrum of the signal (red line). (c) Autocorrelation trace (red stars) and the Gaussian fit (solid black

However, in this case, the signal pulse can produce SPM even for a low power. For a longer pulse duration, the chirp from the stretcher should also be taken into account in the gain analysis since the signal wavelength will be distributed in the temporal domain. In our case, we assume that the signal chirp is negligible compared to the one of the pump since the signal duration is shorter by a factor >10.

3.2. Characterization of the pump

For each delay between the long chirped pump and the short probe, the signal (the probe) overlaps with one slide of the pump owing an instantaneous power and wavelength. Therefore, it is highly important to measure the temporal distribution of the pump wavelength. We measured the chirp rate**, corresponding to the spectral phase,** by spectral interferometry between a long and a short pulse both at the pump wavelength [20]. Accordingly, we modified the set-up. Briefly, a part of the output of the amplifier was injected at the opposite side of the VBG to recompress it to ~300 fs. Then, the chirped pump and the compressed pulse was combined with a beam splitter and the interference pattern was recorded with the OSA. Due to the finite resolution of the spectrometer, the complete interference pattern cannot be measured over the full spectrum. Therefore, a local fringe can be measured directly at the null delay between the two pulses. For more details, we refer the reader to the reference [21] describing the method. For example, the inset in Figure 5.a displays an example of the interference pattern occuring at 1030 nm. In order to get the chirp rate, the spectral location of the fringe was measured as a function of the delay between the long and short pulses (Figure 5.a). The null delay is fixed at 1030 nm. From a linear fit, we deduced a α value of 6.2 ps/nm; i.e the pump wavelengths evolves linearly with time. Combining this value with the spectrum (Figure 1), the

temporal shape can be infered (Figure 5.b). The pulse duration is 55 ps (FWHM) and the temporal shape is modulated with a period of ~14 ps.

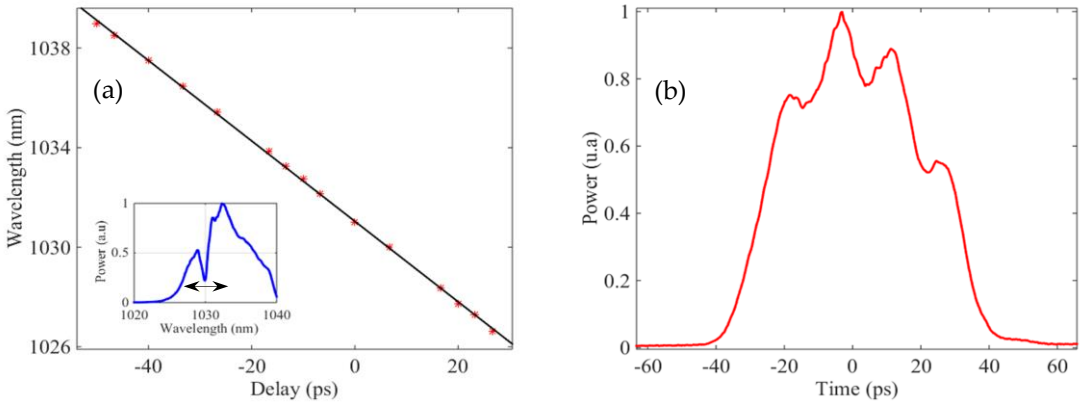

Figure 5. (a) Measurement of the chirp rate by spectral interferometry and its linear fit leading to α=6.2 ps/nm. The inset is an example of the interference pattern. (b) Temporal shape of the pump pulse.

4. Measurement of the amplification and discussion

To measure the instantaneous gain, the chirped pump pulse is injected in the PCF simultaneously with the signal. The delay Δτ between the two pulses is tuned and the amplified spectrum is recorded for every delay separated by 3.3 ps. **To ensure that the pump power launched in the PCF is constant during the complete measurement, we checked that the fluorescence spectrum is identical for each delay.** The amplification has been measured between Δτ~-15 and + 25 ps. For longer delay, we have not detected any clear amplification since the pump power is lower by almost 50 % from its maximum. From the pump average power and the pulse duration (Figure 5.b), the peak power is estimated at ~530 W. The signal average power is ~5 μW. Figure 4.a (blue line) shows an example of an output spectrum when the signal is injected at Δτ around 0 ps. An idler is generated confirming the amplification of the signal. We can also observe some other bands at 952 and 1124 nm resulting from cascaded four wave mixings. Figure 6.a and Figure 6.b show a selection of amplified and idler spectra when the Δτ is tuned from -6.6 ps to +19.8 ps.

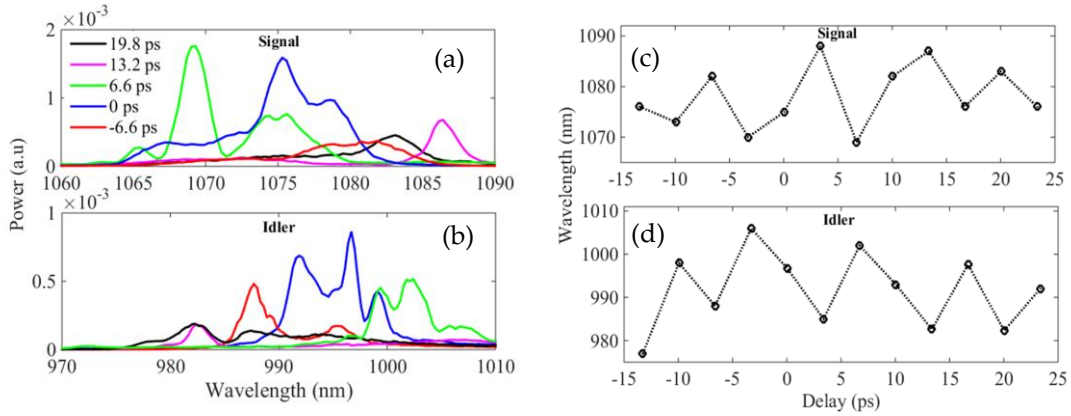

Figure 6. (a-b) Selection of amplified and idler spectra when the delay is tuned from -6.6 ps to +19.8 ps. (c-d) Variation of the signal and idler wavelengths at the maximum amplification as a function of the delay.

The null delay corresponds to the pump wavelength of 1030 nm (Figure 5). However, we cannot accurately define it and we set it when the amplification is maximum near the center of the signal spectrum (blue line in Figure 6.a). For each Δτ, the amplification clearly occurs at a selected wavelength. In addition, the amplified shapes and their bandwidths vary with Δτ since the signal pulse overlaps with a different portion signal of the pump. Therefore, the pump power and the dispersion at the pump wavelength change with the delay and influence the properties of the amplified signal as explained in Section 2. Particularly, the pump temporal shape is modulated around Δτ =0 ps and has a Bell shape (Figure 5.b). Therefore the variation of the wavelengths at the maximum amplification with Δτ (Figure 6.b) is not monotonic and is modulated. The amplification of one given signal wavelength can be achieved at several delays. This behavior is significantly different from the case in which the chirped pump has a constant peak power since only the dispersion parameter changes with time. In this case, the wavelength at maximum amplification evolves monotonically [11].

We also calculated the gain from the spectra of the input and the amplified signal. We remind that the repetition rate of the signal is 76 MHz while the pump one is 1 MHz. Thus, it needs to be taken into account in the gain measurement; the output/input ratio at the signal wavelength does not give directly the net gain of amplification. Indeed, the instantaneous amplification occurs when the pump and the signal temporally overlap while the OSA detects the average power of all the incoming pulses. Therefore, the net gain is derived from $G = S_{amp} / S_{in} \cdot 76$ with S_{amp} and S_{in} the amplified and input signal spectra at the PCF output. Figure 7 displays the evolution of the wavelength at maximum gain as a function of Δτ (black circles) and it shows a similar behavior as in Figure 6.b. For each delay, the maximum gain is very high (red circles in Figure 7) and it ranges from 1.8×10^3 to 4.6×10^5 for signal wavelength extending from ~1068 to ~1088 nm. We checked that the amplifier does not saturate since the gain does not change when the input power of the signal was decreased by a factor 10. In addition, no spectral broadening of the signal by SPM was observed since the amplified spectra was not significantly different at lower power. **Similarly, the measurement of the saturated gain cannot be measured directly since the increase of the signal input power will create SPM.**

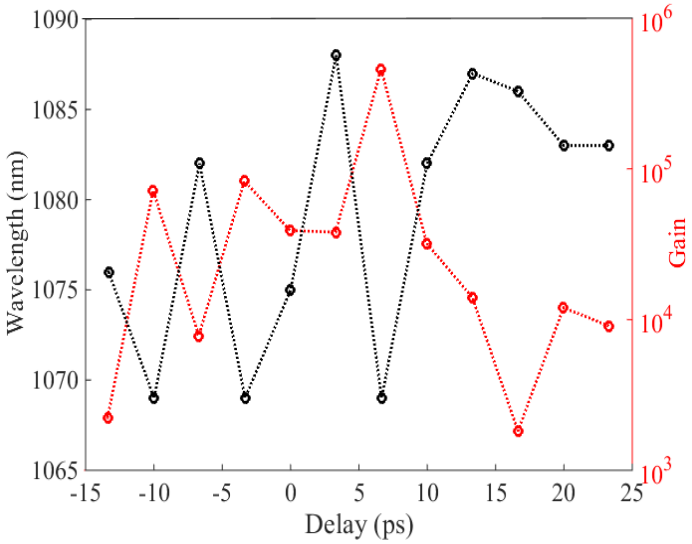

Figure 7. Maximum gain value (red circles) and its corresponding signal wavelength (black circles) as a function of the delay.

5. Conclusions

We presented a pump-probe experiment enabling the characterization of the temporal distribution of the spectral gain in a fiber based optical parametric amplifier pumped by a chirped pump. We showed that the gain value and the amplified spectrum varies importantly when the signal overlaps with a different portion of the pump pulse. This measurement will be very important to include efficiently the fiber based OPA in a laser system delivering ultra-short pulses. For example, when a chirped signal is injected in the PCF with the chirped pump pulse, the temporal evolution of the signal wavelength should match closely the distribution of the spectral gain measured with our method.

Author Contributions: CFD, AI and DB conceived, designed and performed the full experiment; AI and CFD analyzed the data; RD, HMM and PPM designed the PCF; RD and RJ achieved the PCF modeling; RD, PR, HMM and PPM fabricated the PCF and RJ, HMM and PPM characterized it. CFD, PR, HM and DB supervised the project (PCF, experiment and simulation) and contributed to experimental tools and concepts. CFD and DB wrote the manuscript.

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Conflicts of Interest: "The authors declare no conflict of interest."

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