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Chirped pulse amplification in a fiber optical parametric amplifier

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ABSTRACT

Fiber optical parametric amplifiers (FOPAs) have attracted considerable attention during the last decade because of their broad bandwidth, high gain and wavelength-flexibility. In comparison to cumbersome bulky systems, they bring the advantages of all-fiber systems, i.e. reliability, long-term stability and compactness. FOPAs rely on the third-order susceptibility and are characterized by a quasi-instantaneous nonlinear response that involves pump, signal and idler waves. Chirped pulse amplification (CPA) allows to get a high energy amplification and its realization in FOPAs would increase the overall performances of these amplifiers. Such an experimental demonstration has never been reported in the past. In this work, we show for the first time the experimental feasibility of fiber-based optical parametric chirped pulse amplification (FOPCPA) with an all-fibered setup. The stretching/compression stages are realized with a single linearly chirped fiber Bragg grating (LCFBG) used in both directions while the amplification is performed in a CW-pumped FOPA that uses 500 meters of highly nonlinear fiber (HNLF). Fourier transform limited optical pulses at 1550 nm are stretched from 6 ps to 70 ps and then amplified by 22 dB without any spectral or temporal distortions. Experiments are confirmed by simulations carried out by numerical integration of the nonlinear Schrödinger equation with parameters matching those of the experimental setup. For simplicity, this first experimental demonstration is realized in the telecommunication window. By using photonic crystal fibers, one can move the working wavelength around 1 μm .

Keywords: Nonlinear optics, fibers, Bragg gratings, parametric oscillators and amplifiers.

1. INTRODUCTION

Optical parametric amplification (OPA) is a well-known process which conventionally consists in amplifying a weak signal beam in a suitable second-order nonlinear medium by a high intensity pump beam. Combined with chirped pulse amplification (CPA)¹ and termed as optical parametric chirped pulse amplification (OPCPA), it has soon been recognized to be a very attractive technique for high energy amplification of ultrashort pulses^{2,3}. In few millimeter-long crystals, it can be used to amplify broadband pulses with very high gain, high conversion efficiency, low B-integral, good beam quality and high temporal contrast⁴. It has been used to amplify few-cycle pulses up to 90 mJ,⁵ to produce high energy femtosecond pulses⁶ and to seed high-power Nd:glass laser chains^{7,8} for ultra-high intensity experiments⁹. However, these bulk systems are quite cumbersome and complex to implement in experiments. In order to benefit from the ease of use of all fiber systems as well as their reliability, long-term stability and compactness, we propose to investigate the possibility to realize an all-fiber OPCPA system. Such a system was first proposed and numerically investigated by Hanna *et al*¹⁰. However, no experimental demonstration of this concept has been done yet. During the last decade, fiber-optic parametric amplifiers (FOPAs) have focused the attention of many researchers in the field of optical telecommunications because of their broad bandwidth, high gain, wavelength flexibility and wavelength conversion properties^{11,12}. These fiber amplifiers rely on the third-order nonlinearity but have important similarities with OPAs. Their nonlinear response is quasi-instantaneous and a conjugate wave, the idler, is generated during the amplification process^{11,12}.

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In this work, we experimentally demonstrate for the first time to our knowledge a fiber-based optical parametric chirped pulse amplification (FOPCPA) in an all-fiber configuration. Both the stretching and compression stages are realized with the same linearly chirped fiber Bragg grating (CFBG) and the pulse amplification is performed in a continuous-wave (CW)-pumped FOPA. For the sake of simplicity, this first experimental demonstration is realized in the telecommunication window around 1.5 μm . However, there is in principle no limitation to develop a similar system around 1 μm by using photonic crystal fibers as gain medium¹³ and suitable fiber components.

2. EXPERIMENTAL SETUP

Another originality of the setup resides in the use of a single CFBG to stretch and compress the signal pulses, as proposed in ref. [15] for optical delay line purposes. A 15 cm-long grating was written into a hydrogen-loaded standard

single mode fiber by means of the phase mask technique using a continuous-wave frequency-doubled argon-ion laser emitting at 244 nm. The obtained grating is characterized by a chromatic dispersion of about 350 ps/nm. Its refractive index profile was apodized to minimize the ripple on the group delay curve. This one reaches less than a few percents of the mean group delay value. After the inscription process, the grating was annealed during 2 days at 100 °C to stabilize its spectral properties.

Fig. 2 depicts the CFBG reflected spectrum and the corresponding group delay evolution when the light is injected through the short-wavelengths port. These ones are both measured using an optical vector analyzer from LUNA technologies with a wavelength resolution set to 3 pm.

Fig. 2. Reflected amplitude spectrum and associated group delay evolutions (short wavelengths port) of the used CFBG.

In our setup, the signal pulses are obtained from a picosecond oscillator which delivers 6.4 ps full-width at half-maximum (FWHM) transform-limited pulses. Prior to be amplified, the pulses are sent to the short wavelength port of the CFBG. As a result, they are affected by the CFBG chromatic dispersion. The reflected pulses are then stretched to an estimated FWHM of 190 ps so that they are about 30 times larger than the initial duration. The chirped signal and the pump are combined via a 90/10 fiber coupler (90% of the pump goes into the HNLF) and are launched inside the HNLF where the amplification process occurs. After propagation in the HNLF, the amplified pulses are filtered and again fed into the CFBG, this time through the long-wavelengths port. Therefore, assuming that no extra chirp is added during the propagation through the HNLF, this setup ensures a perfect matching between stretching and compression (the chirp seen from both sides of the CFBG should be exactly the opposite) and the output pulses present the same shape as the input ones.

Two polarization controllers are used to achieve orthogonal states of polarization between the beams getting out of the short-wavelengths port and entering in the long-wavelengths one. Indeed, since the CFBG is not perfectly 100% reflective, a small part of the pulses launched in the short-wavelengths port are transmitted and could interfere with the useful signal getting out of the setup. This parasitic signal is removed by using a polarizing beam splitter placed behind the second circulator and aligned along the polarization state of the recompressed signal. Since the central wavelength of the CFBG cannot be easily tuned (mechanical or thermal actuations were preferably not implemented to avoid any undesired wavelength shift), we have adjusted the wavelength and the power of the FOPA pump in order to achieve a perfect phase matching around the CFBG central wavelength (1546.6 nm). This choice combines the advantages of achieving high and nearly flat gain over the spectral width of the signal (0.55 nm). This can be seen in Fig. 3 which depicts the parametric fluorescence spectrum (solid line) and the input signal spectrum (dotted line) recorded using an optical spectrum analyzer ANDO AQ6317B.

Fig. 3. Optical spectrum measured at the FOPA output with signal switched off (solid line). The initial signal spectrum is superposed as a guideline (dashed line).

3. RESULTS AND DISCUSSION

First of all, we have recorded the evolution of the gain as a function of the input signal energy. Corresponding measurements are represented in Fig. 4 in circles. The signal gain starts at 24.8 dB for the lowest energy pulses and rapidly drops beyond 100 fJ pulses, to reach a gain of 12 dB for an input signal energy of 1.5 pJ. The gain obtained for smallest signals (≈ 25 dB) in the linear regime of the amplifier is very close to the gain of a weak monochromatic signal (24.6 dB), represented in dashed line in Fig. 4. It means that the amplifier indeed works in a linear regime for the smallest input energies.

Numerical simulations have been performed to confirm the experimental results. For this purpose, the GNLSE was numerically integrated by using the split step method with experimental parameters taken into account. Higher-order nonlinear effects such as self-steepening have been neglected due to the relatively long pulse duration and the dispersion orders have been limited to the third one. The CFBG was modelled as a purely dispersive element with a dispersion of 350 ps/nm. Note that all nonlinear effects that could occur inside the CFBG have also been neglected due to the extremely low peak power of the pulses. At the output of this dispersive element, we obtained stretched pulses of 193 ps duration at FWHM, in good agreement with analytical relations¹⁶ and the measured pulse-width after the first pass through the CFBG. These chirped pulses are introduced in the FOPA (modelled through the GNLSE) and the output pulse energies are computed. A very good agreement between numerical simulations (solid line) and experiments (circles) is achieved. The saturation of the amplifier is not surprising since the highest input peak power is about 7 mW (assuming 1.46 pJ Gaussian pulses of 193 ps duration at FWHM). If a CW signal of this power was introduced in the amplifier, it would also experience a saturated gain of 15 dB, very close to the 12 dB measured for pulsed signals. This confirms that the lowering of the gain is indeed due to the saturation of the FOPA.

Fig. 4. FOPCPA gain versus signal pulse energy launched into the HNLF for a pump power of 27.6 dBm. Cases I and II correspond respectively to the linear and saturated regimes studied in Fig. 5.

In practice, the results presented in Fig. 4 can be further optimized by modifying the FOPA characteristics. To reach this goal, one can play on the stretching ratio. To illustrate this impact, Fig. 5 depicts the numerically computed gain evolutions for 3 different stretching ratios. Keeping the same amplifier, one can see that, with a stretching ratio equal to 600 (obtained by a well designed CFBG), more than 70 W can be obtained at the FOPA output.

Fig. 5. Numerically computed evolution of the gain versus input energy for 6.4 ps pulses stretched at different ratios.

A clear spectral signature of the amplifier saturation is shown in Fig. 6, where output spectra corresponding to linear and saturated regimes are represented [cases I and II, respectively, in Fig. 4, for respective input energies of 18.9 fJ and 1.46 pJ]. In the linear regime, only one idler wave is generated and the output spectral shape of the signal is quasi-identical to the input one [represented in solid line in Fig. 4]. In the saturated regime, harmonics of the signal and the idler waves are generated in this four-wave mixing process. This multiple-wave interaction associated with the saturation of the amplifier lead to a broadening and a distortion of the output pulses spectrum, as can be seen from Fig. 6. The spectral width is increased up to 1.3 nm, i.e. more than 2 times the initial width (0.55 nm). From these measurements, one sees that the output signal pulses keep their Gaussian temporal shape in the linear regime, while they are strongly distorted in the saturated one.

Fig. 6. Optical spectra in the linear [dotted line, corresponding to case I in Fig. 4], and saturated [dashed line, corresponding to case II in Fig. 4] regimes. (a) Whole spectrum and (b) normalized close-up on the signal pulses, plotted in linear scale. The input signal spectrum has been superimposed in solid line in the (b) picture.

Second-order autocorrelation traces of input and output signals after compression for small-signal and deep saturation regimes are represented in Fig. 7. In the small signal regime, input and output pulses profiles are similar, demonstrating that no additional spectral phase is generated during the amplification process. Assuming a Gaussian shape, we deduced from these traces that the signal pulses duration is 6.4 ps at FWHM and that the time-bandwidth product at FWHM is $\Delta\nu \cdot \Delta t \approx 0.43$, i.e. the pulses are nearly Fourier transform-limited. In saturated amplification, due to the increased spectral width, a pulse shortening is observed. We found a pulse duration of 4.3 ps at FWHM in this case, by assuming a Gaussian shape. Due to the strong distortions of the output signal spectrum we cannot accurately estimate the time-bandwidth product, but we expect that the saturation of the amplifier combined with the beating with other waves should lead to additional spectral phase.

4. CONCLUSIONS

In this work, we have reported the first experimental demonstration of fiber-based optical parametric chirped pulse amplification. Picosecond Fourier-transform pulses at 1550 nm were successfully amplified by 24.6 dB without any spectral or temporal distortions. These performances were reached with a single linearly chirped fiber Bragg grating used for both the stretching and compression operations. The experimental results were confirmed by numerical simulations obtained with the nonlinear Schrödinger equation.

By using photonic crystal fibers one could move the working wavelength around 1 μm [13], obtain a broader spectral bandwidth thanks to the high nonlinearity of these fibers, and then scale this technique to the femtosecond regime.

Fig. 7. Measured autocorrelation traces of the input signal (solid line), the amplified signal with 18.9 fJ input energy [dotted line, case I in Fig. 4] and the amplified signal with 1.46 pJ input energy [dashed line, case II in Fig. 4].

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