All-fiber chirped pulse amplification using highly-dispersive air-core photonic bandgap fiber

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Abstract: We show, for the first time to our knowledge, all-fiber chirped pulse amplification using an air-core photonic bandgap fiber. Pulses from a wavelength- and duration-tunable femtosecond/picosecond source at 10 GHz were dispersed in 100 m of dispersion compensating fiber before being amplified in an erbium-doped fiber amplifier and subsequently recompressed in 10 m of the anomalously dispersive photonic bandgap fiber. Pulses as short as 1.1 ps were obtained. As air-core fibers present negligible nonlinearity, the presented configuration can potentially be used to obtain ultra-high pulse peak powers. A study of the air-core fiber dispersion and dispersion slope is also presented.

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References and links
1. Introduction

Optical pulse sources based on single-mode fibers are flexible and potentially low-cost devices, which yield diffraction limited beams with little or no need for alignment that can also offer low electrical power consumption and air-cooled operation. All these assets make such sources compare favorably with their bulk counterparts. However, as fiber-based sources confine light to areas of ~50 \(\mu\)m\(^2\) over at least a few meters, the optical nonlinearity distorts pulses with high peak powers. Typically, nonlinearity threshold is reached at a peak power of ~1 kW divided by the fiber length in meters, while megawatt peak powers are obtainable with bulk sources. To overcome this problem and increase the peak power achievable with fiber systems the well-known technique of chirped pulse amplification can be employed [1-5].

The chirped pulse amplification technique was first demonstrated using solid state, bulk-coupled lasers and amplifiers [1]. It consists of chromatically dispersing the optical pulses, amplifying the temporally broadened pulses, and recompressing them in a dispersive medium with the reciprocal chromatic dispersion. Each dispersive medium can be a pair of diffraction gratings [1,2], an optical fiber [1-3], or a fiber Bragg grating [4,5]. When an optical fiber is used as the pulse stretcher, the chirp can result from the fiber dispersion only or from dispersion in combination with self-phase modulation.

Chirped pulse amplification has also been demonstrated with fiber pulse sources and amplifiers, with all three types of dispersive elements [2,4,5]. In one experiment [2], a configuration was used that employed an erbium-doped fiber amplifier (EDFA), a fiber as the stretcher, and a pair of bulk diffraction gratings as the compressor. 420-fs pulses were obtained after the grating pair, with 3 nJ energies being achieved at the EDFA output. In other experiments [4,5], fiber Bragg gratings were used to stretch and compress the pulses while EDFAs were used for amplification. Pulses of 408 [4] and 900 fs [5] were obtained with respective energies of 3 and 1.6 nJ. The advantages of using all-fiber components are that simpler configurations that do not require alignment are obtained. However, again the problem is that the achievable peak powers are limited by fiber nonlinearity.

Much higher optical nonlinearity thresholds are obtained in air-core photonic bandgap fibers (PBFs) [6-8]. In these recently developed fibers, guidance is obtained via diffraction off layers of air holes in the glass cladding. Most of the light, however, propagates through air in the core, making the fiber nonlinear coefficient ~1000 times lower than that of conventional fibers [8]. The expected maximum peak powers for linear pulse propagation are, therefore, accordingly higher. Due to the diffractive nature of guidance, PBFs transmit only a limited spectral band, the center and width of which vary with the profile of the cladding holes. As expected, air-core PBFs present negligible material contribution to chromatic dispersion. Nevertheless, the waveguide dispersion varies throughout the transmission bandgap and can be considerably high near its edges. Dispersion values of up to ~400 ps nm\(^{-1}\) km\(^{-1}\) were reported [6].

Here we report for the first time, to the best of our knowledge, an all-fiber chirped pulse amplification system where recompression is achieved in an air-core PBF. Pulses at a wavelength of ~1.55 \(\mu\)m, with durations of hundreds of femtosecond were linearly stretched in 100 m of dispersion compensating fiber (DCF) to tens of picoseconds and subsequently compressed down to ~1 ps in the PBF. A characterization of the fiber dispersion is also presented, revealing extremely high dispersion and dispersion slope values.

2. Experimental configuration

The experimental configuration used for chirped pulse amplification as well as for characterizing the dispersion of the air-core PBF is shown in Fig. 1. An optical source yielding pulses that were wavelength-tunable from 1535 to 1565 nm and duration-tunable from ~8 ps to ~400 fs was employed. This source is described in detail elsewhere [9], and consisted of a 10-GHz electro-absorption modulator, seeded by a cw tunable external-cavity semiconductor laser, that was followed by a nonlinear soliton compressor based on Raman amplification. A fiber polarization controller allowed for adjustment of the pulse polarization.
The pulses had average powers of up to 150 mW at the source output. They were attenuated in an optical attenuator (OA) to avoid optical nonlinearities and subsequently stretched in 100 m of DCF with a dispersion at 1.55 µm of -130 ps nm⁻¹ km⁻¹.

The chirped pulses were then amplified in an EDFA consisting of two stages. The first stage was optimized for low-noise operation and accepted input average powers of tens of microwatts. The second stage was designed for high-power operation and gave output average powers of up to 3 W. A fiber pig-tailed isolator was used at the EDFA output to prevent undesired back-reflections from reaching the gain fiber. The amplified pulses were finally recompressed in the 10-m anomalously dispersive PBF, the cross-sectional profile of which is shown in Fig. 2(a). This fiber was directly spliced to the isolator fiber and had an overall loss of ~2.2 dB at 1.55 µm (including splice loss), although lower losses are achievable with air-core PBFs [8]. The transmission bandgap of the PBF stretched from ~1410 up to ~1600 nm. Figure 2(b) shows experimental transmission and group-velocity dispersion spectra around the wavelength of interest, of two pieces of PBF obtained in the same pull as the fiber used in the present work. The dispersion was measured with the modulation phase-shift method, in a commercial chromatic dispersion test module (Agilent 86037C), and presented values in excess of 1000 ps nm⁻¹ km⁻¹. As the PBF was birefringent, the pulse polarization was adjusted using the fiber polarization controller located in the pulse source. A lens was used at the output end of the PBF to collimate the beam and direct it to a second-harmonic generation autocorrelator (AC) or an optical spectrum analyzer. As the AC detected pulses at a single linear polarization, the pulses propagating at each PBF principal axes could be independently characterized using a half-wave plate at the AC input.

![Fig. 1. Experimental configuration used for all-fiber chirped pulse amplification and PBF dispersion characterization.](image)

![Fig. 2. Cross-sectional profile of the PBF (a) and transmission and dispersion spectra of two PBF pieces similar to that used in this work (b).](image)

### 3. PBF dispersion characterization

As mentioned in the introduction, the bandgap nature of the PBF transmission profile leads to a strong waveguide contribution to the fiber dispersion. In particular, the dispersion is expected to be normal at shorter wavelengths and anomalous at longer wavelengths, crossing zero somewhere in between.

The dispersion of the PBF used is expected to be similar to those shown in Fig. 2. However, in order to optimize the setup for chirped pulse amplification, the PBF dispersion at ~1.55 µm was thoroughly characterized using short pulses. First, the DCF length in the setup was optimized in a cutback experiment where ~400-fs input pulses at ~1560 nm were used...
and the output pulses were monitored in the AC. The pulses were launched in a single principal axis of the PBF. It was found that 100 m of DCF yielded the shortest output pulses. Then, the PBF was removed from the configuration and the length of DCF adjusted again to yield the shortest output pulses. This time, 11.8 m of the DCF were used. By combining the results from the two cutback measurements, the PBF dispersion at 1560 nm was calculated to be \(\approx 1146 \text{ ps nm}^{-1} \text{ km}^{-1}\). This very high dispersion value allows for the pulses to be considerably broadened in the DCF before being amplified. It should be noted that the dispersion at the other PBF principal axis was also characterized, being \(\approx 115 \text{ ps nm}^{-1} \text{ km}^{-1}\) higher. This latter polarization, however, was not used in any of the following experiments.

Although 100 m of DCF yielded the shortest output pulses when the PBF was in the setup, these pulses where still considerably chirped, having pulse durations of \(\approx 1.3\) ps and presenting shapes that deviated from the expected sech\(^2\) profile. This can be accounted for by the contribution of higher order dispersion. In fact, considering that the dispersion is likely to be zero at some point between 1.41 and 1.55 \(\mu\)m and has such a high value at 1560 nm, a high dispersion slope is expected.

To examine the dispersion slope, the solitons from the pulse source were adjusted to a duration of \(\approx 1.7\) ps and were spectrally tuned while the output pulses were monitored in the AC. Figure 3 shows the pulses at the DCF input and at the PBF output for pulse wavelengths of \(\approx 1556\), \(\approx 1558\) and \(\approx 1561\) nm. As can be seen, the PBF-output pulses at 1561 nm are nearly as short as the corresponding DCF-input pulses, while the pulses at 1556 nm are considerably broadened at the PBF output. To quantify the PBF dispersion slope, the pulse wavelength was left at 1556 nm and a piece of standard telecommunication fiber (STF) was added to adjust the dispersion. It was found that 77 m of STF were necessary to yield the shortest output pulses. It was therefore calculated that the PBF dispersion at 1556 nm was \(\approx 1031 \text{ ps nm}^{-1} \text{ km}^{-1}\). Assuming that the PBF dispersion linearly increases between 1556 and 1560 nm, the dispersion slope can be, thus, estimated to be \(\approx 29 \text{ ps nm}^{-2} \text{ km}^{-1}\).

![Fig. 3. Autocorrelation traces at the PBF output (red) and at the DCF input (blue) for pulse wavelengths of \(\approx 1556\) (a), \(\approx 1558\) (b), and \(\approx 1561\) nm (c).](image)

### 4. Chirped pulse amplification experiments

After the dispersion characterization and the DCF adjustments described in the previous section, the setup was used for stretched pulse amplification. For this purpose, the pulses launched into the PBF were kept at the polarization characterized above, and the tunable semiconductor laser of the pulse source was set to 1556 nm, while the pulse duration at the source output was varied. As expected, inspection of the pulse spectrum at different points in the configuration revealed no observable nonlinear effects occurring in the DCF or the PBF. It was found that the pulses experienced some soliton self-frequency shift within the source and, therefore, shorter pulsers had longer wavelengths. Note that this feature was taken into account in the previous section and all wavelengths mentioned were experimentally measured at the source output. For chirped pulse amplification, this feature meant that with longer pulses...
(centered at ~1556 nm), the DCF and PBF dispersions were not balanced and significant pulse broadening occurred. On the other hand, when the source was set to yield shorter pulses, the spectrum moved towards 1560 nm, where the dispersions are matched and allow better recompression in the PBF.

Figure 4 shows the best pulse compression obtained. In this case, the pulses from the source (blue trace in Fig. 4(a)) measured ~500 fs (assuming a sech² pulse profile). The autocorrelation of pulses after the first stage of the EDFA is shown in Fig. 4(b). Note that Fig. 4(b) has a scale that is 10 times larger than that of Fig. 4(a) and that, therefore, these pulses are extremely broad, exceeding the measurement window available in the autocorrelator. In order to estimate the pulse duration at the DCF output, a simulation was used. The simulation assumed an unchirped pulse at the DCF input and, using the DCF length and dispersion, delayed each pulse spectral component accordingly to obtain the stretched pulse duration. For the 3-dB pulse spectral width of ~5.5 nm the simulated stretched pulse duration was ~70 ps. As the pulse source operates at 10 GHz repetition rate, adjacent pulses at the DCF output should significantly overlap. The autocorrelation of the pulses at the PBF output are seen in red in Fig. 4(a). The autocorrelation 3-dB width is measured to be ~1.8 ps, corresponding to 1.2 ps pulse durations if a sech² profile is assumed. Output pulses were linearly polarized. Additional compression of the pulses was not possible due to the high value of the PBF dispersion slope. Further shortening the pulses in the source resulted in distorted and broader pulses both due to the high dispersion slope and due to the soliton self-frequency shift away from the setup zero average dispersion.

The PBF output pulses shown in Fig. 4(a) had ~1.1 W average power when the EDFA was set to 3 W due to losses in the optical isolator and in the PBF. As the output spectrum suggests that ~95% of the output energy is in the pulse, it is estimated that the peak power is ~87 W. In the future we expect to increase the peak power to at least tens of kilowatts by dropping the pulse repetition rate. As the PBF nonlinear coefficient is ~1000 times lower that of a conventional fiber, we expect the propagation to be linear even at these power levels.

To improve the output pulse temporal profile, a tunable bandpass filter with a 3-dB spectral width of 3 nm was introduced between the DCF and the EDFA. The filter spectral position was adjusted to give the shortest and least distorted pulses. The filter allowed the pulses from the source to be used with their minimum duration without output pulse distortion. Figure 5 shows a comparison of the output pulses obtained with and without the use of the filter, for DCF-input pulses of 400 fs. Figure 5(a) shows the autocorrelation traces. The output pulses obtained were linearly polarized and had a sech² duration of ~1.1 ps when the filter was used, while pulses measured ~25 ps after the first stage of the EDFA. The average output power was ~1.1 W as before. Figure 5(b) shows the spectra of the pulses with
and without the filter. As can be seen, the optimal filter position approximately coincides with the measured setup zero average dispersion. The 3-dB spectral width when the filter is used is ~2.8 nm, resulting in a time-bandwidth product of ~0.38, which approaches the 0.32 value of unchirped sech² pulses. The spectrum obtained with the use of the filter suggests that ~100 % of the output energy is in the pulse, which in this case leads to a peak power of ~100 W.

5. Conclusions

All-fiber stretched pulse amplification was demonstrated with compression being obtained in an air-core photonic bandgap fiber. 10-GHz-repetition-rate pulses at 1.55 μm from a picosecond/femtosecond pulse source were linearly stretched in 100 m of DCF, amplified in a 3-W EDFA, and then recompressed in 10 m of the air-core fiber. Output pulses were as short as 1.1 ps and presented a low chirp when a bandpass filter was employed. Due to the high repetition rate, peak powers were moderate (~100 W) but can potentially be increased to at least tens of kilowatts if lower repetition rates are used. Dispersion characterization of the PBF was also presented, revealing a dispersion as high as ~1146 ps nm⁻¹ km⁻¹ at 1560 nm, and a dispersion slope of ~29 ps nm⁻² km⁻¹.

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