Multi-kilowatt, all-fiber integrated chirped-pulse amplification system yielding 40× pulse compression using air-core fiber and conventional erbium-doped fiber amplifier

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Abstract: We present a totally fiber integrated chirped-pulse amplification system using air-core photonic bandgap fiber and a conventional erbium-doped fiber amplifier. ~40-ps input pulses, generated in a Mach-Zehnder modulator, were stretched and spectrally broadened in a dispersion-shifted fiber before being amplified and subsequently compressed in 10 m of anomalously-dispersive photonic bandgap fiber to yield ~960 fs pulses. The system gives multi-kilowatt peak powers while the amplifier nonlinearity threshold is as low as ~150 W. Higher peak powers could be obtained by the use of an amplifier with higher nonlinearity threshold.

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References and links

1. Introduction

Chirped-pulse amplification (CPA) is a powerful technique for escalating the peak powers achievable with an optical pulse source when distortion caused by amplifier nonlinearity is the limiting factor. It was first demonstrated by Strickland and Mourou [1] using a bulk solid-state laser and amplifier, an optical fiber as the stretcher, and diffraction gratings as the compressor. CPA is particularly attractive for use with fiber-based pulse sources, as the high confinement in a conventional fiber limits the achievable peak power-fiber length product to ~1 kW.m. As most devices are at least a few meters long, peak powers rarely exceed 0.5 kW. CPA systems designed for fiber pulse sources need to be equally built in all-fiber format not to negate assets such as compactness and alignment-free operation. All-fiber CPA was obtained with use of fiber Bragg gratings for stretching and compression, yielding sub-picosecond pulses with nanojoule energies [2,3]. However, as the fiber gratings are incorporated in conventional fibers, nonlinearity once again imposes peak-power limitations.

Unlike conventional fibers, in the recently-developed air-core photonic bandgap fibers (PBFs) [4-6] most of the light travels through air, allowing for much higher peak powers to be achieved before nonlinearity-led pulse distortion is observed. In these fibers, guidance is obtained through diffraction off the several layers of holes present in the cladding rather than through Fresnel reflection. As a consequence, transmission occurs only within a limited wavelength range related to the hole distribution. Although the material chromatic dispersion in PBFs is negligible, strong waveguide dispersion wavelength dependence is observed and is a consequence of the bandgap nature of the transmission. Typically, high negative and positive dispersion values are obtained in the short- and long-wavelength transmission edges, respectively, with zero dispersion occurring somewhere in between.

CPA using PBF for pulse compression was first demonstrated [7] using a totally fiber integrated system consisting of a femtosecond/picosecond tunable fiber source, a dispersion compensating fiber for linear pulse stretching, an erbium-doped fiber amplifier (EDFA), and 10 m of air-core PBF. In this system, 500 fs pulses were stretched to nearly 100 ps and recompressed to ~1.1 ps, with further compression hindered by the high dispersion slope of the PBF. As the pulse source operated at 10 GHz repetition rate, the achieved peak powers were moderate (~100 W) despite the relatively high (~1 W) average output powers. Much higher peak powers (~0.82 MW) were achieved in a later CPA experiment [8] using a PBF. The high powers obtained resulted from the use of a specialty amplifier consisting of a photonic crystal large-mode-area Yb-doped fiber, which yielded ~30 kW peak powers even without the CPA system. However, in this configuration a bulk-coupled, solid-state pulse source and bulk optical elements were used. In fact, the very nature of the amplifier prevents complete fiber integration.

In this paper, we present a CPA system that is totally fiber integrated and provides net pulse compression by a factor 40. Pulses of the order of 40 ps from a Mach-Zehnder modulator are stretched via dispersion and self-phase modulation in a dispersion-shifted fiber (DSF), amplified in a conventional EDFA and compressed down to ~960 fs in a PBF. Multi-kilowatt pulses are achieved at the PBF output despite an EDFA nonlinearity threshold of ~150 W.

2. Experimental configuration

The experimental configuration of the all-fiber CPA system is shown in Fig. 1. Input pulses at 1547 nm were obtained by amplifying a cw, tunable, external cavity semiconductor laser in a 22-dBm output power EDFA and modulating it in a 20-GHz Mach-Zehnder modulator driven with 35-ps electrical pulses at 50-MHz repetition rate. The pulses were then amplified in a 20-dBm EDFA so that SPM could be observed in the subsequent 3.95-km DSF, which at 1547 nm had dispersion and dispersion slope of -1.71 ps nm⁻¹ km⁻¹ and 0.07 ps nm⁻² km⁻¹, respectively. This fiber also had a modal area of 46.2 µm² and a measured nonlinear refractive index of 2.29x10⁻²⁰ m²/W. The stretched pulses were amplified in a third EDFA (EDFA3) yielding up to 2 W average output power. This EDFA is a commercial model from IPG Group.
and consists of a double-cladding, single-mode, solid silica Ytterbium-Erbium-doped fiber that has an experimentally-determined nonlinearity threshold of \( \sim 150 \, \text{W} \).

The amplified pulses were finally linearly compressed in the 10-m PBF (Crystal Fibre model AIR-10-1550), the input of which was directly fusion spliced to a conventional fiber. The transmission bandgap of this fiber stretched from \( \sim 1.41 \) to \( \sim 1.60 \, \mu\text{m} \), with a net loss (including that of the splice) of \( \sim 2.2 \, \text{dB} \) around 1.55 \( \mu\text{m} \). The PBF dispersion and dispersion slope at 1547 nm were \( \sim 940 \, \text{ps nm}^{-1} \, \text{km}^{-1} \) and \( \sim 25 \, \text{ps nm}^{-2} \, \text{km}^{-1} \), respectively. Further information about this fiber can be found in Ref. [7]. As the PBF was birefringent, a polarization controller was used to launch pulses in a single principal axis.

Note that nearly all optical components used in the setup were in the fiber format. The few components that were not constructed with fiber, namely the modulator, the tunable laser, and pump diodes and isolators within the EDFAs, were pigtailed by their manufacturers. No bulk optical elements were needed and total fiber integration was achieved. Pulses were characterized using an optical spectrum analyzer, a streak camera and a second-harmonic generation autocorrelator.

![Fig. 1. Experimental configuration of the multi-kilowatt, all-fiber CPA system.](image)

3. Results and discussion

The launched power into the DSF was optimized by monitoring the PBF output pulses with the autocorrelator. Controlling this power adjusted the SPM-induced spectral broadening occurring in the DSF and, consequently, the amount of chirp in the stretched pulses. An average power of 65 mW was found to be optimum. Figure 2 shows streak camera traces and spectra for the pulses before and after the DSF. Pulses before this fiber had a \( \sim 38\)-ps duration and a spectral 3-dB width of 0.19 nm. SPM in the DSF broadens the pulse spectrum to \( \sim 7.5 \) nm and dispersion stretches the pulse duration to \( \sim 85 \) ps.

![Fig. 2. Streak camera trace (a) and spectrum (b) taken before (blue) and after (red) the DSF.](image)

From the pulse durations and repetition rate the peak power into the DSF can be calculated to be \( \sim 30 \, \text{W} \). With such a power and with the DSF parameters quoted above, it can be estimated from equations derived from numerical methods [9] that the maximum achievable compression factor would be \( \sim 71 \), obtained with an optimum fiber length of 4.7 km. Note, however that this estimate neglects higher order dispersion and requires that the
compressor length be adjustable. As the PBF dispersion slope is non negligible and its length
was not optimized, one can expect a reduced compression factor in the present experiment.

The blue traces in Fig. 3 show the optimized autocorrelation and spectrum of the
compressed pulses obtained in the PBF output, with an amplifier average output power of ~1
W. The autocorrelation has a full-width at half maximum of ~1.5 ps, corresponding to 960 fs
if a sech² profile is assumed. This corresponds to a high input-to-output net compression of
39.6×. The pulse quality is good with a low pedestal, but low-amplitude shoulders are observed
and stretch for ~20 ps. These shoulders and the inability to further compress the pulses are
consequences both of the high PBF dispersion slope, that introduces a nonlinear chirp in the
pulses, and of the use of unoptimized PBF and DSF lengths [9]. The latter problem can be
solved with small changes to the configuration, while the former would require a different
PBF. The output pulse spectrum is very similar to that taken in the DSF output (Fig. 2(b)) and
identical to that obtained in the EDFA3 output, indicating that the minor spectral changes
observed occur in the amplifier. The output pulses were observed to be linearly polarized.
Operation in the other PBF principal axis was also achieved with very similar pulse
characteristics, but with the pulse wavelength shifted to 1549.3 nm, due to the different PBF
dispersion.

Fig. 3. Autocorrelation (a) and spectrum (b) of the PBF output pulses without (blue) and with
(red) use of the bandpass filter.

Improved pulse quality, with removal of the shoulders, could be obtained by introducing
a pigtailed tunable bandpass filter between the DSF and EDFA3, as shown in red in Fig. 3.
The filter had a 3-dB bandwidth of 3 nm and its optimum spectral position was found to be
~1550 nm. It is possible that the nonlinear chirp induced in the PBF is partially compensated
for by the nonlinear chirp induced by SPM towards the edge of the pulse spectrum, which
would explain the optimum filter position being shifted relative to the pulse spectral center.
With the filter, the EDFA3 average output power had to be reduced to 440 mW, as the use of
the filter shortens the pulses in the amplifier input. The compressed pulses presented a
duration of 1.96 ps (sech² profile assumed). In addition to the shaping induced by the filter,
the pulse spectrum presents some distortion resulting from amplifier nonlinearity.

The average output powers obtained without and with the bandpass filter were 600 and
270 mW, respectively, of which ~61 and ~97% correspond to power in the pulses (the
remainder being accounted for by EDFA amplified spontaneous emission and unmodulated
laser light). For the case in which the filter was used, the pulse peak power can be calculated
by assuming a sech² profile and multiplying the average power by the ratio between pulse
period and duration, times a factor 0.88 that accounts for the pulse profile. This procedure
yields a peak power of ~2.0 kW.

It is difficult to directly estimate the peak power in the case without the filter because of
the presence of the pulse shoulder. We, therefore, estimated it by measuring in the
autocorrelator the pulses with the filter and observing the trace amplitude increase when the
filter is removed and the configuration re-optimized. We assume that the autocorrelation signal is proportional to the second-harmonic signal and, thus, bears a quadratic dependence with the pulses peak power. Note that this method may be somewhat inaccurate, as it has been shown that the response from a photomultiplier tube is not absolutely linear [10]. However, we believe the errors should be minimal for the small dynamic range required for this estimation. The highest peak power for the case in which the filter was not used is, therefore, ~3.3 kW. This represents an increase by a factor 22 relative to the maximum achievable power straight from EDFA3. The use of an EDFA with a higher nonlinearity threshold would instantly result in an increase in output peak power.

5. Conclusions
A totally fiber integrated chirped pulse amplification system was demonstrated that utilizes an air-core photonic bandgap fiber and a conventional erbium-doped fiber amplifier. The result is a compact, simple and reliable configuration yielding 40× input-to-output pulse compression, pulses as short as 960 fs, and peak powers of up to ~3.3 kW. The achieved peak power was limited by the nonlinearity threshold power of the amplifier (~150 W). An increase in this threshold would result in even higher peak powers. Shorter pulses can be obtained through optimization of the fiber lengths or of the dispersion profile of the photonic bandgap fiber. The use of a bandpass filter resulted in improvement in the pulse profile with only a slight peak power reduction.

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