All-fiber integrated \( \sim 10 \) kW peak power ultrashort optical pulse source based on compression in aircore photonic band gap fiber

C. J. S de Matos, R. E. Kennedy, \(^{a, b}\) and J. R. Taylor

Femtosecond Optics Group, Physics Department, Imperial College, Prince Consort Road, London SW7 2BW, United Kingdom

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We demonstrate an all-fiber integrated, \( \sim 10 \) kW peak power, \( \sim 1 \) ps optical pulse source at a wavelength of 1.55 \( \mu \)m based on compression in aircore photonic band gap fiber. A 10 GHz pulse train was modulated at 10 MHz in a Mach–Zehnder amplitude modulator with a \( \sim 1 \) ns transmission window before stretching in 100 m of dispersion compensating fiber, amplifying, and recompressing in 10 m of aircore photonic band gap fiber. Numerical simulations show that if the aircore fiber dispersion slope could be made negligible, the achievable peak power would be increased by a factor of approximately 2. © 2004 American Institute of Physics. [DOI: 10.1063/1.1826227]

The many advantages of all-fiber sources may facilitate industrial and research applications of high peak power ultrashort pulses.\(^1,5\) All-fiber sources are simple and reliable as there is no need for bulk optical alignment and complicated cooling systems. Furthermore, the efficiency of fiber amplifiers and the use of mass produced components make fiber lasers potentially cheap to run and to manufacture. However, since most all-fiber systems contain a few meters of fiber, the attainable peak powers are currently limited to \( \sim 1 \) kW by pulse distortion due to optical nonlinearity. Hybrid fiber-bulk systems based on chirped pulse amplification (CPA) have been demonstrated using grating pairs\(^6\) and, more recently, aircore photonic band gap fiber (PBF)\(^7\) compressors, obtaining peak powers of over \( \sim 10 \) and 0.86 MW, respectively. However, since these systems are not fully fiber integrated, many of the above-discussed all-fiber advantages are lost.

The use of recently developed aircore photonic band gap fiber for high peak power delivery is of current interest due to the low nonlinearity and low loss of these waveguides. The former advantage has enabled the generation of megawatt solitons\(^8\) and the delivery of high energy nanosecond pulses.\(^9\) Furthermore, the dispersive properties of PBFs are such that high or low, normal or anomalous dispersion can be obtained at the operating wavelength, which is of particular importance for ultrashort pulse propagation and/or compression. In addition, PBFs can be fusion spliced to conventional fiber, thus facilitating all-fiber integrated high peak power ultrashort pulse sources through CPA techniques. The highest peak power reported using such a system is 3.3 kW,\(^10\) in which bandwidth was generated by self-phase modulation in a conventional fiber before amplification of the chirped pulses and compression to 960 fs in a PBF. The first CPA experiment using an aircore PBF compressor was also a fully fiber integrated system in which pulses were linearly dispersed in a dispersion compensating fiber (DCF) before subsequent amplification and recompression.\(^11\) In this case, however, the peak power obtained was relatively low (\( \sim 100 \) W) due to the high repetition rate used. In this letter we describe a further fully fiber integrated source based on temporal stretching in DCF, with a higher duty cycle than Ref. 11 obtaining \( \sim 10 \) kW of peak power and a compressed pulse duration of \( \sim 1 \) ps. Numerical simulations of the system show reasonable agreement with experiment. In addition the role of the dispersion slope of the aircore PBF is numerically investigated by simulating the system in the absence of dispersion slope. In this case the simulated peak power is increased by a factor of approximately 2.

The experimental configuration used is shown in Fig. 1. A 10 GHz soliton train was modulated at 10 MHz with a \( \sim 1 \) ns transmission window, stretched in 100 m of DCF, amplified in a chain of erbium doped fiber amplifiers (EDFAs) and compressed in 10 m of anomalously dispersive aircore PBF. The 10 GHz femtosecond/picosecond tunable soliton source used is described elsewhere,\(^12\) and is based on adiabatic soliton compression of \( \sim 10 \) ps pulses produced by a continuous wave tunable external-cavity semiconductor laser modulated by a 10 GHz electroabsorption modulator. The source was operated at a wavelength of 1548 nm and was duration tunable from 8 ps to 400 fs. An attenuator was required to reduce the power to within the operational power range (\( \sim 90 \) mW) of the Mach–Zehnder amplitude modulator (MZAM). Polarization controller 1 (PC1) was used to optimize the input polarization to the MZAM, which was driven at 10 MHz and synchronized to the 10 GHz source. The modulator transmission window could be tuned from

\(^{a}\)Electronic mail: richard.kennedy@imperial.ac.uk

FIG. 1. Experimental configuration.
$-0.22 \text{ ps nm}^{-2} \text{ km}^{-1}$ at 1.55 μm, to higher order dispersion. Figure 2 shows the autocorrelation traces of the pulses at the output of the 10 GHz pulse source (dashed) and at the aircore fiber output (solid). Using a sech² fit, the pulse durations were estimated to be 700 and 880 fs, respectively. (b) Streak camera traces of the pulse train just before EDFA3 (solid) and of theMZAM transmission window (dashed).

$\sim 0.5$ to $\sim 2$ ns by adjusting the width of the driving electrical pulses. Pulses were subsequently amplified in a low noise erbium doped fiber amplifier (EDFA1) to partially compensate for losses in the modulator while keeping the peak power below the threshold for nonlinearity in the following fibers. The pulses were stretched in 100 m of DCF, which had a dispersion of $-130 \text{ ps nm}^{-1} \text{ km}^{-1}$ and a dispersion slope of $-0.22 \text{ ps nm}^{-2} \text{ km}^{-1}$ at 1.55 μm. A length of standard telecommunications fiber (STF) was used to fine tune the system dispersion compensation. The chirped pulses were amplified in EDFA2, which was again optimized for low noise operation, and EDFA3, which was optimized for high power operation and had a saturated output power of 10 W. A fiber pigtailed optical circulator provided isolation to prevent backreflection in the PBF ends from reaching the gain fiber. The amplified chirped pulses were compressed in the 10 m of anomalously dispersive aircore PBF, which was fusion spliced to the circulator fiber. The PBF used (Crystal Fibre AIR-10-1550) had an estimated dispersion of $950 \pm 50 \text{ ps nm}^{-1} \text{ km}^{-1}$ and an estimated dispersion slope of $25 \pm 1.5 \text{ ps nm}^{-2} \text{ km}^{-1}$ at 1548 nm and an overall loss (including splice loss) of $\sim 2.2$ dB. Polarization controller 2 (PC2) was used to optimize the polarization into the birefringent aircore PBF, and the light out of the PBF was found to be linearly polarized. Finally, the system output was collimated and directed into a second-harmonic generation auto-correlator or an optical spectrum analyzer.

The duration of the input pulses from the 10 GHz fs/ps tunable pulse source was adjusted to obtain the shortest PBF output pulses which did not show significant distortion due to higher order dispersion. Figure 2(a) shows the autocorrelation trace of the optimum input pulses. Assuming a sech² pulse shape the pulses had a full width at half maximum (FWHM) of $700 \text{ fs}$. Note that the measured bandwidth (FWHM) of these pulses was $4.6 \text{ nm}$, corresponding to a pulse FWHM of 550 fs. Since the input pulse source produces solitons, which are necessarily transform limited, the difference between the measured pulse duration and the transform limited pulse duration was attributed to dispersion in the fiber connecting the output of the source to the auto-correlator. With the output power from EDFA3 set to just below the damage threshold for the circulator ($\sim 3 \text{ W}$), theMZAM transmission window was adjusted to obtain the highest duty factor that did not exhibit nonlinearity. A transmission window of $\sim 1$ ns was found to be the optimum setting allowing 10–11 pulses through in each modulator cycle. A streak camera trace of the pulse train just before EDFA3 is shown in Fig. 2(b). The pulse duration at this point is $\sim 40$ ps. The figure also shows theMZAM transmission window. It can be seen that the amplitude modulation apparent in the pulse train is due to the profile of the transmission window.

Figure 2(a) shows an autocorrelation of the system output for the best compression obtained. In this case the optimum length of STF for dispersion compensation was found to be $\sim 135 \text{ m}$. Assuming a sech² pulse profile, the pulse duration is $880 \text{ fs}$. The inability to recover the input pulse duration is attributed to the dispersion slope of the aircore PBF and, to a lesser extent, to the DCF. Higher order dispersion may also account for the sidelobes apparent in the autocorrelation trace of the aircore output.

From an analysis of the spectrum at the system output, we estimate that 95% of the output energy is in the pulse train, with the remainder in ASE and in spurious radiation from the fs/ps tunable pulse source. The average power after the PBF was measured to be 1.36 W, and assuming 10 pulses per pulse group, the estimated peak power was 13 kW.

We modeled the system using the numerical method described in Ref. 13. The simulation included the effect of dispersion up to the third order but neglected nonlinearity. The resulting output pulse intensity profile using the simulation parameters specified in Table I is shown in Fig. 3(a) and has a peak power of 9.9 kW and a FWHM of 1.09 ps. The discrepancy between the experimentally estimated and numerically simulated pulse duration and peak power is partially due to the assumption of a sech² pulse shape in the experimental case, which underestimates the pulse duration and therefore overestimates the peak power. The experimentally and numerically obtained autocorrelations are shown in Fig. 3(b).
Fig. 3(b), and are in reasonable agreement. While we attempted to avoid significant pulse distortion due to nonlinearity, some nonlinearity may still be present in EDFA3, and may partially account for the small discrepancy between the autocorrelations in Fig. 3(b). The various assumptions made in modeling the system (see Table I) may also contribute to this difference. Note that Fig. 3(b) indicates that the experimentally obtained pulses were shorter than the numerically simulated pulses and therefore suggests that the numerically obtained peak power of 9.9 kW is an underestimate of the actual peak power.

To investigate the limitations imposed on the output pulse characteristics by the higher order dispersion in the aircore fiber, we then set the PBF dispersion slope in the simulation to zero. The resulting pulse profile is shown in Fig. 3(a) and has a peak power of 18.9 kW and a FWHM of 660 fs. The small difference between input and output pulse duration is accounted for by the dispersion slope of the DCF. This result, together with recent developments in high dispersion, low dispersion slope PBFs\(^{14}\) means that the peak power could be increased by a factor of approximately 2 by simply replacing the PBF.

In conclusion, a \(\sim 10\) kW peak power \(\sim 1\) ps duration all-fiber integrated pulse source at a wavelength of 1.55 \(\mu\)m based on chirped pulse amplification with compression in aircore photonic band gap fiber was demonstrated. This result represents an improvement by a factor of 3 over previously demonstrated all-fiber CPA systems. Simulations show that if the higher order dispersion of the aircore fiber could be made negligible, the peak power would be increased by a factor of approximately 2. This result, together with recent developments in high dispersion, low dispersion slope PBFs means that the peak power could be increased to \(\sim 19\) kW by simply replacing the PBF. The source described here can immediately supersede its bulk solid state laser counterparts in a number of industrial and scientific applications.

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