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450kW, all fibre, picosecond Chirped Pulse Amplification system based on a large mode area fibre Bragg grating compressor

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1. Introduction

Chirped pulse amplification (CPA) is a well known technique for producing high power short optical pulses[1,2] suitable for nonlinear optical experiments. Using such techniques with bulk amplifier systems it is possible to produce femtosecond optical pulses with terawatts of peak power[3].

In a CPA system a short transform limited optical pulse is first chirped by a highly dispersive element and thereby temporally stretched by factors of up to 10000. The pulse is then amplified to a high energy before being recompressed back to its initial duration at the system output by a device of opposite dispersive characteristics to the pulse stretcher. In this manner high peak powers are avoided, and thereby the limiting effects of nonlinearity within the amplifier, thus massively extending the peak powers attainable. Pulse stretching and compression is usually performed using bulk optic devices such as a diffraction grating pair. However in order to obtain the temporal stretching factors required grating separations of order 1 m are required, making such systems large and cumbersome to use.

Recently the CPA technique has been applied to pulse systems based on erbium doped fibre amplifiers opening up the possibility of the development of robust, compact CPA systems based on linearly chirped fibre Bragg gratings (FBGs). The main advantage of FBGs is that they are highly dispersive and can thus provide suitable time-delays in only centimetre lengths of fibre. Using a 12 cm grating Galvanauskas *et al.* recently demonstrated a CPA scheme capable of producing 2 ps picosecond pulses with 300 nJ of energy and peak powers of order 150 kW[4]. One drawback to the use of FBGs is that they are intrinsically nonlinear and at high powers this nonlinearity will degrade the pulse quality. In Galvanauskas' experiment the limiting factor to producing μJ pulses was the nonlinear phase-shift caused by pulse propagation in the fibre preceding the grating. This length can clearly be reduced but then one runs into the problem of nonlinearity inside the grating itself. As has been recently shown nonlinear effects in gratings[5] can become significant at intensities as low as $5\,\mathrm{GW/cm^2}$. The power level corresponding to this threshold clearly depends on the mode area of the fibre. Hence it is advantageous to use fibres with large mode areas but which are still singlemoded at the operating wavelength. Recently such a fibre was developed for use in high power amplifiers in order to reduce the effect of the nonlinearity as well as allowing for more efficient energy extraction[6]. By slightly modifying the composition of this fibre we are able to fabricate a photosensitive fibre suitable for grating writing. These gratings were then used as the compressor for a CPA system based around an erbium fibre amplifier chain to produce an all-fibre based source of high power (> 400 kW) short pulses.

2. Experimental Results

The schematic of our experimental setup is shown in Fig. 1. The pulse source is a passively mode-locked erbium fibre ring laser producing transform limited 1.5 ps soliton pulses at a repetition rate of 1.67 MHz at (tuneable) central wavelengths around 1534 nm. The soliton pulse energy is 10 pJ. The pulses were then stretched to a duration of ≈ 1 ns after reflection from a 20 cm linearly chirped grating FBG1 (described below). After being stretched the resulting pulse train was amplified in an EDFA to an average power of 10 dBm and then passed through a pulse selection system based on an AOM with fast 100 ns rise and fall times. The pulse selector could be used to step down the repetition rate of the pulse train to a user definable subharmonic of the laser repetition frequency. In the experiments described herein we selected a pulse repetition rate of 10 kHz. The selected pulses were then amplified in a 3m long, low noise optical preamplifier to an energy of ≈ 100 nJ before being launched through a second gated AOM (used to reduce the affect of ASE induced gain saturation) and then into a final stage, double pass amplifier of 80cm length constructed from large mode area erbium doped fiber which allowed for efficient energy extraction and low optical nonlinearity[6]. The energy of the pulses at the amplifier system output was $\approx 15\,\mu$J. By appropriate polarisation control the pulses were then launched onto grating FBG2, recompressed and output from the system. Note that the pulse energy launched into FBG2 could be controlled by rotation of a half wave plate (see Fig.1). The coupling efficiency from the final stage amplifier output to compressor output was around 15%.

The reflection characteristics of gratings FBG1 (stretcher) and FBG2 (compressor) are shown in Fig. 2. Both gratings were written using a scanning phase-mask technique[7] and both gratings were apodised so as to reduce the ripples in the time-delay. The first grating was 20cm long with a bandwidth of 4nm and was linearly chirped with a slope of -442 ps/nm. The peak peak reflectivity of the grating was approximately 10%. The second grating was 10 cm long with a bandwidth of 2 nm with opposite chirp (439 ps/nm) to the first grating and 90% reflectivity. FBG2 was written in a novel, specially fabricated photosensitive large mode area fibre with an NA of ≈ 0.05, a cutoff wavelength of 1300 nm and an estimated mode area of $450\,\mu m^2$, i.e. between 4 to 10 times that of fibre conventionally used to write FBGs. We therefore anticipated a corresponding increase in achievable output pulse energies and powers relative to previous all-fibre CPA systems.

We first examined the quality of the pulse amplification and compression with low powers launched into the recompression grating FBG2, optimising the source wavelength for minimum linear distortion. Pulse recompression to 4.0ps was readily achievable representing a pulse broadening by a factor of 2.7 due to gain shaping, spectral filtering and the slight mismatch between the dispersions of FBG1 and FBG2. This pulse quality was maintained up to a reflected pulse energy of 900 nJ, corresponding to a peak power of ≈ 225 kW (see Fig. 3a). At higher output pulse energies nonlinear pulse distortion became apparent as shown in Fig. 3b where we show the corresponding output autocorrelation function and spectrum for an output pulse energy of $1.7\,\mu$J. Note that the pulse is much squarer due to nonlinear reshaping but that the pulse compression still appears to be reasonable. If we assume a $sech^2$ shaped pulse the pulse FWHM is 3.8 ps. The peak power of these pulses corresponds to 450 kW. The nonlinear distortion is more evident in the spectral domain where the side-lobes are more distinct and the onset of Raman scattering is observed

As the pulse energy is increased further nonlinear effects in the fibre Bragg grating began to play a more significant role in the pulse shaping. For pulse energies above $2\,\mu$J the reflected pulse had a large pedestal which contained a significant fraction of the pulse energy.

Numerical modelling shows that the nonlinearity dominates the linear compression only over the last section of the grating where the pulse is close to fully recompressed. This can lead to more pronounced effects in apodised gratings since the the pulse recompression takes place further into the grating structure. Reducing the length of the 1cm apodised sections in the gratings used in our experiment should therefore lead to increases in peak output power. It is also important to ensure that the centre wavelength of the input pulse is chosen such that the pulse is reflected from as close as possible to the front end of the grating.

3. Conclusion

We have designed and fabricated photosensitive large mode area fibre Bragg gratings and demonstrated their use use in a compact, robust all-fibre based CPA system. We have obtained good quality picosecond pulses with pulse energies in the microjoule regime and peak powers as high as 450 kW. The results represent a significant advance upon previous all fibre CPA systems and our simulations indicate that by further optimisation of the gratings significantly higher pulse energies and powers should be achievable.We believe such practical sources to have great potential for use in a wide range of nonlinear optics applications.

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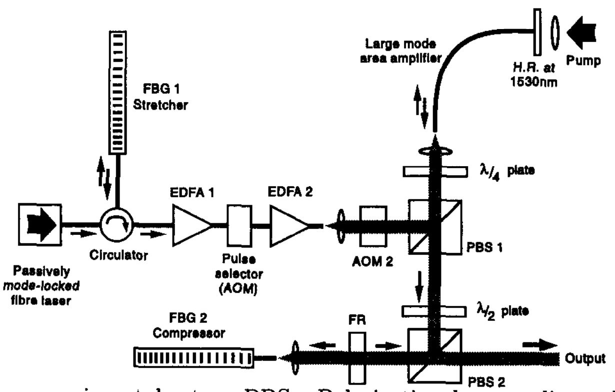

Fig. 1. Schematic of the experimental setup, PBS - Polarisation beam splitter, FR – Faraday rotator. See text for more details.

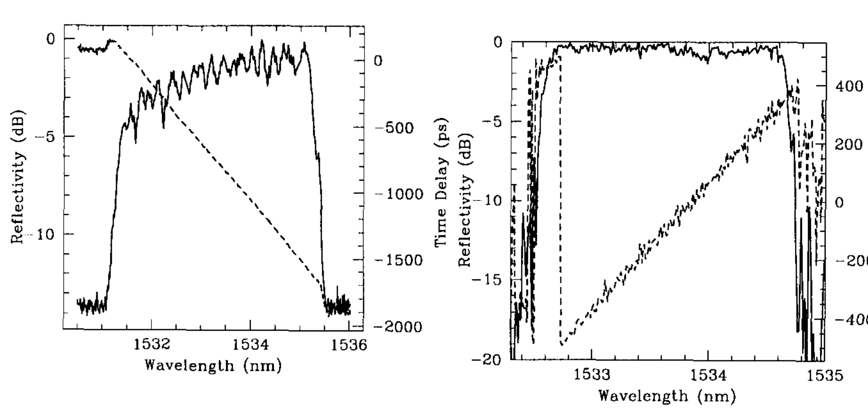

Fig. 2. Fig. A is the reflection spectrum of the first chirped grating (FBG1) while Fig. B shows the second grating (FBG2). The solid lines show the reflectivity while the dashed lines give the time delay. The rolloff in reflectivity in FBG1 is due to unavoidable cladding mode losses.

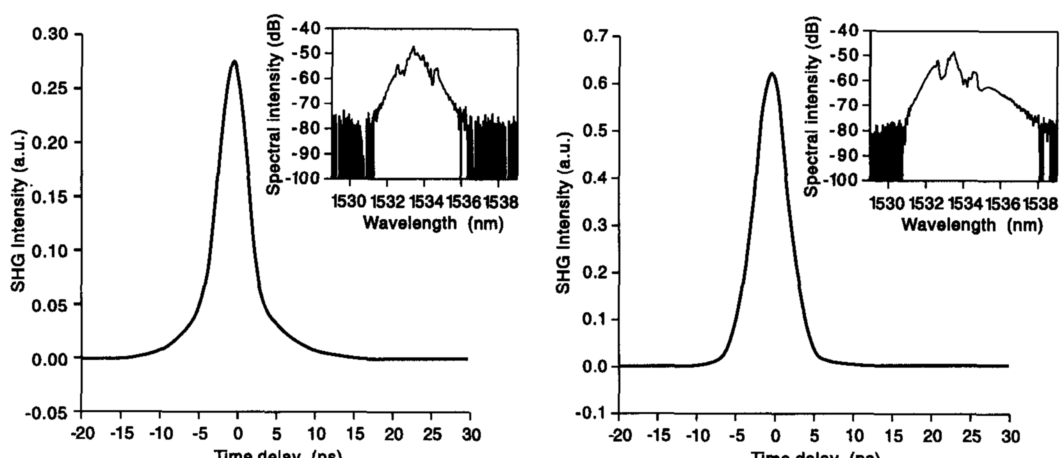

Fig. 3. (A) Low power (900nJ) pulse autocorrelation trace (pulse width 4.11 ps). (B) High Power (1.7 μJ) autocorrelation trace (pulse width 4.11 ps). The measured pulse widths are for an assumed $sech^2$ shape. The inserts show the measured pulse spectra.