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158µJ Pulses From a Single Transverse Mode, Large Mode-Area EDFA

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Abstract

We report the amplification of 10pJ-100pJ, semiconductor diode pulses up to an energy of 158µJ and peak powers >100kW in a multi-stage fibre amplifier chain based on a single-mode, large mode-area erbium doped amplifier design. These results represent the highest single-mode pulse energy ever extracted from any doped fibre system.

Sources capable of delivering high energy pulses of nanosecond order duration at 'eye safe' wavelengths beyond 1500nm are required for a wide range of practical applications from LIDAR through to laser marking. A semiconductor seed source followed by an erbium doped fibre amplifier (EDFA) cascade would seem an attractive means to such an end, providing for a compact, reliable system. Recently progress towards this solution to such applications has been made with >100µJ, 10ns pulses being reported from a multimode, diode-pumped Er/Yb fibre amplifier [1]. However, for many of these applications a single transverse mode-output beam is a desirable, if not fundamental requirement. To date conventional single-mode EDFA fibre designs, optimised for small signal gain and high pump efficiency, have restricted the attainable pulse energies to less than 10µJ [2,3]. For applications requiring higher pulse energies source choice has therefore been limited to more cumbersome and expensive bulk laser options.

To obtain significantly increased output energy characteristics one needs to consider what can be done in terms of fibre design to achieve improved energy storage within the EDFA. Increasing the mode-field and dopant areas of the EDFA should result in a greater number of ions participating in the amplification process and a reduction of the small signal gain occurring within the amplifier, which can restrict the inverted population depletion through gain saturation by amplified spontaneous emission (ASE). The improvement such increases make has been shown through the numerical modelling of low repetition-rate high-energy EDFA pulse amplification in reference [4] and in the work of reference [5] where a multimode EDFA produced pulse energies of 0.4mJ. With the restriction of maintaining a single transverse mode at the signal wavelength, greater single-mode areas can be achieved through a reduction in the fibre numerical aperture along with an increased core size, though such changes are limited by the requirement of maintaining a practical level of bend-loss. We have recently reported the development and application of a large mode area EDFA in an experimental chirped-pulse amplification (CPA) system [6] where the increased mode area also reduces the nonlinear effects that limit pulse recompression in these systems. In this paper we report an examination of the limits to pulsed energy extraction in these large mode-area fibres through the amplification of 10ns-100ns pulses, resulting in the highest single-mode pulse energies extracted from any doped fibre amplifier system, to our knowledge.

igure 1 shows a schematic diagram of the experimental setup. A laser diode source, providing 1mW cw at 1534nm, was directly modulated to produce 10ns-100ns square pulses with resultant pulse energies of 10pJ-100pJ. These were passed into a two stage, high gain EDF pre-amplifier and then finally launched into the large mode-area EDFA stage. The three amplifier stages were

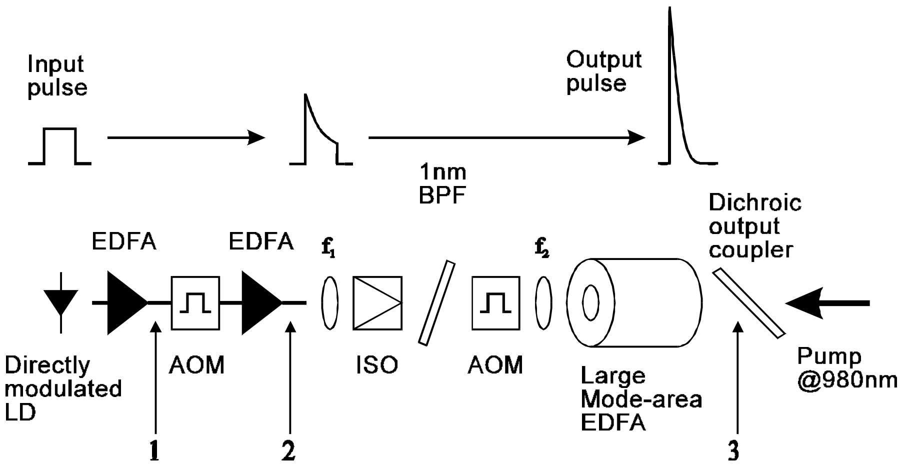

Figure 1: Experimental set-up. EDFA: Erbium-doped fibre amplifier, AOM: Acousto-optic modulator, ISO: Bulk isolator, BPF: Wavelength tunable band-pass filter, f_1,f_2: Focussing optics matched to the NA of the large mode area EDFA. Points 1, 2 and 3 correspond to the positions of temporal measurements presented in figure 3.

separated by two acousto-optic modulators (AOMs) with 100ns rise times, triggered to gate through the pulses whilst blocking ASE from passing between adjacent stages. A 1nm bandpass filter was placed after the two pre-amp stages, prior to the large mode-area EDFA, to eliminate the small amount of ASE in the time slot of the pulse. For a 100ns pulse at a repetition rate of 1kHz this resulted in a pulse energy of 3µJ incident on the final stage. With the pulse width reduced to 10ns pulse energies of 1.4µJ were still being extracted. The coupling optics between the preamplifier and large mode area final stage were chosen to accommodate their large NA mismatch so that a coupling efficiency of 75% was achieved. The large mode area amplifier was end pumped in a backward direction with up to 1.1W of 980nm radiation from an argon ion pumped Ti:Sapphire laser, and amplified output signal separated from the incident pump using a dichroic beam splitter.

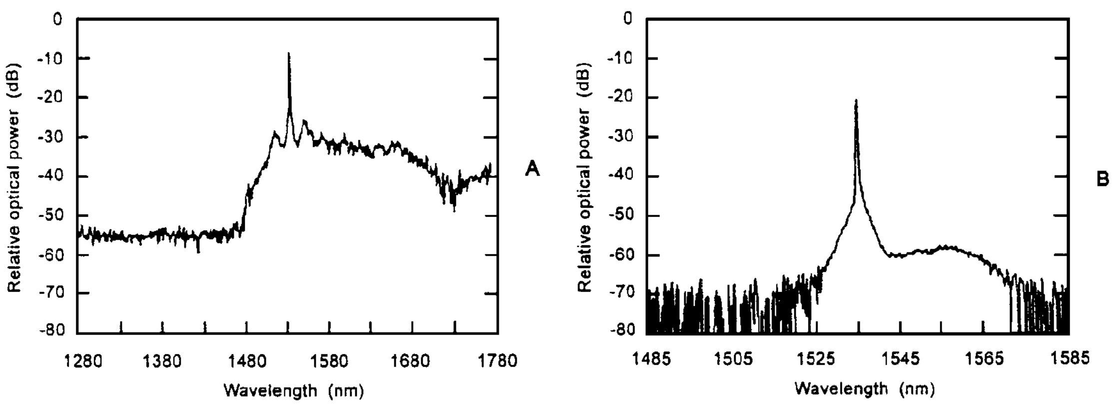

Figure 2: 100ns pulse output spectra from fibres A and B at a repetition rate of 1kHz, corresponding to pulse energies of 158µJ and 123µJ respectively.

Two fibres were tested as the final stage each angle polished at both ends to reduce reflections. The first fibre, A, was doped to 400ppm erbium, had an NA of 0.066, a calculated field mode area of $\approx 310\mu m^2$ and a cutoff wavelength of 1450nm giving a single mode at the signal wavelength. A 4.5m length of this fibre was used coiled with a 30cm diameter, observed to be sufficient to alleviate the problems of bend loss. Figure 2A shows the output spectrum obtained for a 100ns initial pulse width at a repetition rate of 1kHz (found to be the optimum rate, see figure 4). With an output power as high as 160mW the ASE power generated during the gain recovery period estimated to be less than 2mW, corresponding to a pulse energy of 158µJ. The spectrum from fibre A shows a significant proportion of the pulse energy has been scattered into Raman generated spectral components. In order to reduce the interaction lengths over which this nonlinear effect occurs a significantly shorter amplifier length was required, so a second fibre was fabricated with higher erbium-ion dopant concentration. This fibre, B, had a dopant concentration of 1500ppm, an NA of 0.07, $275\mu m^2$ field mode area, and a single mode cutoff wavelength at 1400nm. With the amplifier length reduced to 1.45m of fibre B 123µJ output pulses were obtained (130mW of output power with an estimated 7mW of ASE). Figure 2B shows the resulting output spectrum with no noticeable signs of nonlinearly generated components.

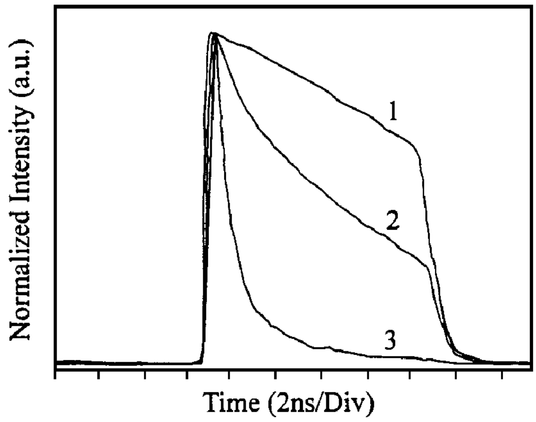

Figure 3: Temporal pulse forms obtained at points 1, 2 and 3 in the system (see figure 1) for a 10ns square input pulse.

On reducing the input pulse width to 10ns, we obtained estimated pulse energies of 148µJ from fibre A and 118µJ from fibre B, values which were only slightly reduced from those obtained for 100ns input pulses. The reasons for this became clear when the pulse temporal forms were observed using a PIN diode and oscilloscope after each amplifier in the system. These are shown in figure 3. The significant shaping effects that result in the low level of the pulse trailing edge occur as the stored energy was depleted by the front edge of the pulse passing through the amplifier, suggesting that almost all of the extractable energy was being taken up by the pulse. The initially square 10ns pulse was found to have narrowed to 6ns after the pre-amps and to almost 1ns at the final stage

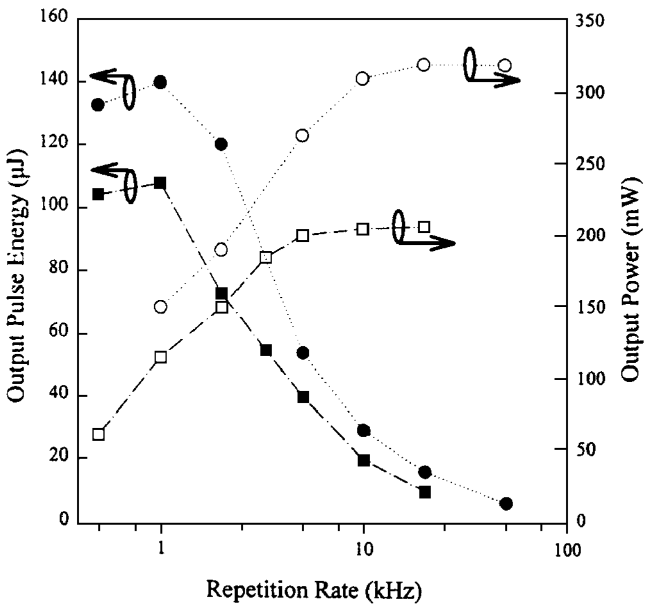

Figure 4: Output power (open data points) and pulse energy (filled data points) versus input repetition rate for 10ns (squares) and 100ns (circles) input pulses.

output. With an energy of 118µJ this corresponds to a peak power of over 100kW.

The variation of the output power with the pulse repetition rate in fibre A was recorded in figure 4. It can be seen that the greatest pulse energy was reached at a repetition rate of 1kHz. At repetition rates higher than this the fibre is being pumped for shorter periods between pulses so less energy is stored. However, below 1kHz the ASE saturates the gain, preventing any further increases in energy storage and hence energy extracted. The maximum extracted averge power for each fibre, 310mW and 207mW respectively, was achieved at repetition rates above approximately 20kHz although at this point the pulse energies had been reduced to less than 20µJ.

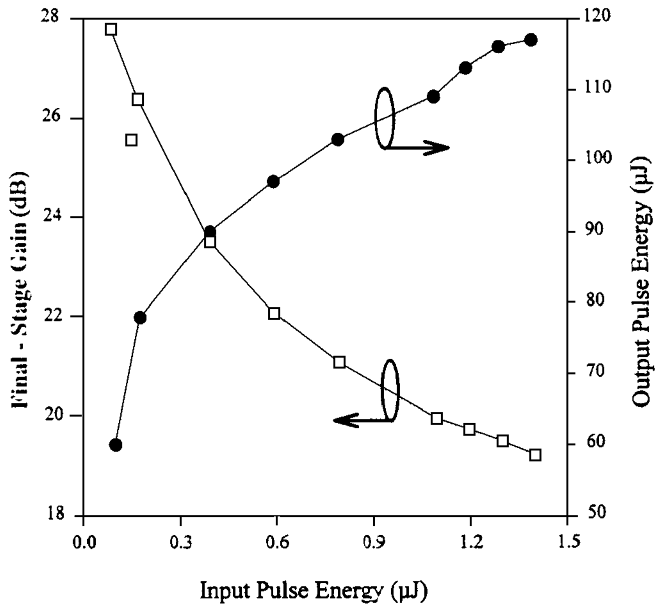

Figure 5: Output pulse energy (black circles) and last stage gain (white squares) versus input pulse energy for 10ns input pulses at 1kHz repetition rate.

By controlling the preamplifier it was possible to obtain a plot of incident pulse energy versus output energy and the corresponding amplifier gain, as shown in figure 5. The observed saturation of the output energy further confirms that most of the available stored energy was being extracted. It was noted that the final stage amplifier was producing a gain of over 19dB at the point of maximum energy extraction and that gains of 28dB were still being achieved for smaller signals.

In conclusion, we have produced pulse energies of 158µJ at a repetition rate of 1kHz from an EDFA pumped with 1.1W at 980nm. 10ns pulses of 10pJ energy were amplified to energies of 118µJ with a spectrally clean output, demonstrating an input-to-output system gain greater than 70dB. The resultant pulse narrowing to 1ns implies peak pulse powers over 100kW. Using this large mode-area EDFA we have achieved an increase of greater than 10dB over previously reported results from an erbium-doped amplifier [3], energies that to our knowlege represent the highest extracted from any single mode doped fibre system. These high energies and peak powers from a system that is well suited to diode pumping schemes, suggest the potential of our design as a compact source for applications such as supercontinuum generation and LIDAR. This fibre design also results in significantly reduced nonlinearities as compared to a standard EDF and hence would be particularly well suited to applications such as CPA, where self phase modulation can be a limiting factor to the recompressed pulse energy.

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