P2.13	GENERATION OF 111kW (0.5mJ) PULSES AT 1.5mm USING A GATED CASCADE OF THREE FIBRE AMPLIFIERS

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Abstract The amplification of low repetition rate, 1.534μm pulses from a DFB laser diode to peak output powers of 111kW and energies of 0.5mJ is demonstrated. The optimised amplifier chain comprised two high efficiency single-mode, 980nm (40mW) pumped erbium-doped fibre amplifiers (EDFAs) separated from a multimode, 978nm (1.5W) pumped EDFA by an acousto optic gate.

Introduction High power and mJ-energy pulses at the relatively eye-safe wavelength past 1.5μm find applications in sensors, range finding and Lidar. With the advent of the EDFA it is attractive to generate such pulses by simply amplifying low-power diode-laser pulses using the high gains available. Attempts to obtain high power have been reported[1] using a two stage erbium-doped amplifier employing an optical gate, resulting in a gain and pulse energy of 49dB and 1.05nJ. To further increase the pulse energy into the mJ range requires the use of multimode fibre amplifiers. To date 16dB of amplification has been demonstrated in an erbium-doped multimode amplifier[2], for a cw input signal of -11.84dBm.

This letter demonstrates the combination of both single-mode and multimode fibre amplifiers in a gated cascade to generate low-repetition-rate, high peak-power pulses. Comparable performance to a diode-pumped, Q-switched Nd:YAG laser[3] is obtained although at the more favourable wavelength of 1.5μm. Single-mode and multimode fibre geometries were employed to optimise both amplifier gain and stored energy, taking into account the available input signal and pump power. The optimum fibre parameters were determined using an extension of a numerical model which has previously been employed for cw signal amplification[4]. As is well known in large cascaded laser amplifiers, it is essential to prevent the ASE build up from saturating the amplifier if a large gain is required. This can be achieved by using saturable absorbers between stages, or in the case of pulse systems, to isolate the amplifiers using a synchronously-timed gate. In this experiment the whole system was configurated for amplification of a ~10ns pulse and thus its was possible to use an acousto-optic modulator as the gate.

Experiment The experimental configuration is shown in fig 1. The first two EDFAs (EDFA 1 and

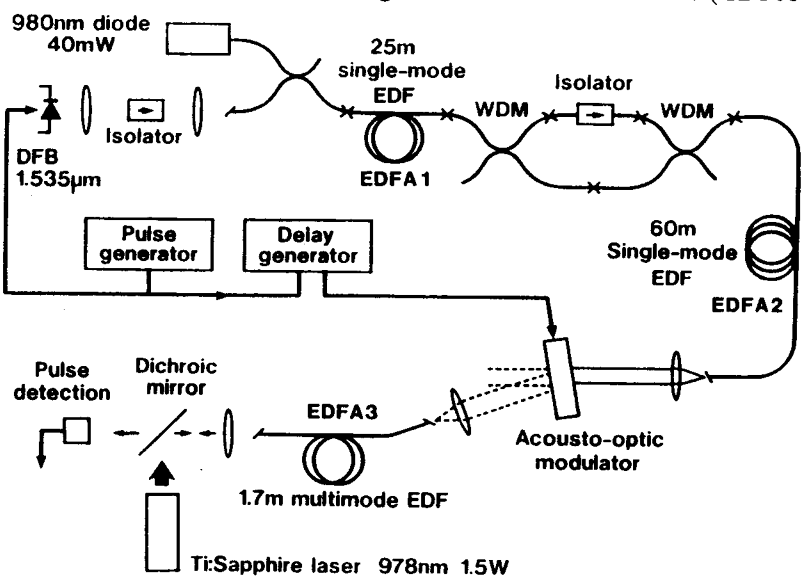

Figure 1
Experimental set up.

2) were constructed from single-mode fibre and were designed for maximum amplification of a short, low energy pulse, typically $\approx 10^{-11}$J. The amplifying fibre was characterised by a germano-silicate core, an NA of 0.24, cutoff wavelength of ~920nm and erbium absorption of 0.95dB/m at 1.536μm. EDFA 1 and 2 used different fibre lengths[8] (25m and 60m), separated by a polarisation-independent isolator (signal insertion loss 1dB) to suppress the backward-travelling ASE and thus prevent saturation at the input to the amplifier. The amplifiers were pumped in series using a common 40mW 980nm diode and, since the isolator has a very high loss at the pump wavelength, two WDM couplers with insertion losses at the pump/signal wavelengths of 0.11dB/0.31dB and 0.16dB/0.31dB were included to provide a low-loss by-pass for the pump. The resultant forward insertion losses between the two amplifiers were ~0.6dB at the pump wavelength and ~2.1dB at the signal wavelength. The isolation in the reverse direction was greater than 30dB over a 50nm bandwidth centred at 1540nm. This configuration has given excellent results for cw, small signal amplification and can yield gain as high as 54dB[5]. The third EDFA (EDFA3) acts as a power amplifier and had a geometry optimised for an input pulse of energy $\approx 10^{-7}$J. To obtain mJ pulses it is obviously necessary to store energy in the amplifier of this order and this requirement determines the core volume for a given Er^{3+} concentration. The stored energy was achieved in our case by employing a multimode fibre in order to increase the core area. In addition, the NA was reduced to minimise the number of fibre modes and thus the ASE. We employed a germano-alumino-silica erbium-doped multimode fibre of length 1.7m with an erbium concentration of 1450ppm, numerical aperture of 0.12 and core diameter of 25μm which supported ~20 modes at both pump and signal wavelengths. EDFA3 was pumped with 1.5W at 979μm from a Ti:Sapphire laser. Since the fibre is multimode, in principle one of the new multi-stripe 980nm diode lasers could be employed. The signal source was a DFB laser diode operating at 1.534μm and allowed 5-500ns pulses with a maximum peak power of 1.53mW to be launched into EDFA1. The signal and pump source were copropagated in EDFAs 1 and 2 and counterpropagated in EDFA3.

Analysis of the ASE spectra indicated that EDFAs 1 and 2 exhibited a net maximum gain at 1.534μm with a 3dB bandwidth of 2.1nm, whilst the gain of EDFA3 was centred at 1.532μm with a 3dB bandwidth of 4.8nm. This slight mismatch in gain spectrum results in a small decrease (~2dB) in unsaturated gain, but will not significantly affect the saturated pulse output.

An acousto-optic modulator (AOM) was employed between EDFA2 and EDFA3 to gate the optical signal. The output beam from EDFA2 was collimated through the AOM and the first-order defracted beam launched into EDFA3. The transmission loss was 3.4dB and the extinction ratio of 41dB effectively prevented any significant ASE power coupling from one amplifier to the other when the AOM was in the off state. The rise time of the optical gate was 300ns.

Results The cascade amplifier was characterised for a range of parameters, including pump power, input pulse power, pulse width and repetition rate and also the gate duration.

The maximum output power obtained was 111kw using a 10ns quasi-square input pulse of peak power 1.53mW at a repetition frequency of 400Hz. This output corresponds to a net amplifier gain of 78.6dB. The launched pump powers in this case were 40mW and 1.5W for EDFA1/2 and EDFA3 respectively. The amplification was split such that the output peak power from EDFA2 was 88W, corresponding to 47.6dB gain in these two sections. The AOM was driven with a gate width of 300ns. Owing to the coupling loss between the two EDFAs, the resultant input pulse to EDFA3 had 40W peak power and the peak gain of EDFA2 was 34.4dB. However, because of the high peak powers in EDFA3 the output power decreased with time, (figure 2) showing clearly that the pulse was significantly depleting the population inversion. The average output pulse power over its 10ns duration was 34.5kW, giving a pulse energy of 0.35mJ. The peak output power measured was limited by the 2ns risetime of the 10ns pulse. However, it is clear that significantly higher output powers should be possible for a shorter duration pulse, particularly if the small mismatch in spectral gain peak noted earlier could be elimiated.

Pulse amplification was measured as a function of pulse repetition frequency and a 3dB gain saturation observed at a frequency of 2kHz, as shown in figure 3. This relatively low frequency is a consequence of the low pump rate and the long metastable life-time of the Er^{3+} ion in silica glasses

(τ_f ~ 10ms) as well as the high pulse energy which significantly depletes the gain medium.

Figure 4 plots the dependence of the output pulse energy and time-averaged gain as a function of input pulsewidth in the range 5 to 500ns at a constant repetition rate of 400Hz. The average gain is seen to decrease by 16dB with increasing pulsewidth. However, this is accompanied by an increase in output pulse energy which can approach 0.5mJ for a 500ns pulsewidth. Figures 5a and 5b show the dependence of gain characteristics on both the first and second stage pump powers. In both cases the gain was saturated, indicating the system was well optimised.

Theoretical simulations of the system response have been carried out employing an extension of a cw model[4] and parameters representative of the fibres employed. Considering a 10ns input pulse with 2ns risetime and 1.53mW peak power, we predict a peak output power of 155kW and total energy of 0.46mJ, which is in reasonable agreement with the experiment. Further, we predict peak output powers of 900kW for a 100ps input pulse in the same configuration, or a 10ns, 1MW pulse when a third multimode power amplifier pumped by a 10W diode is added to the chain.

Conclusion By employing in a cascade of three EDFAs separated by an acousto-optic gate we have amplified a 10ns, 1.53mW pulse from a DFB laser to a peak power of 111kW (0.34mJ). It is predicted that peak output powers up to 1MW should be achievable.

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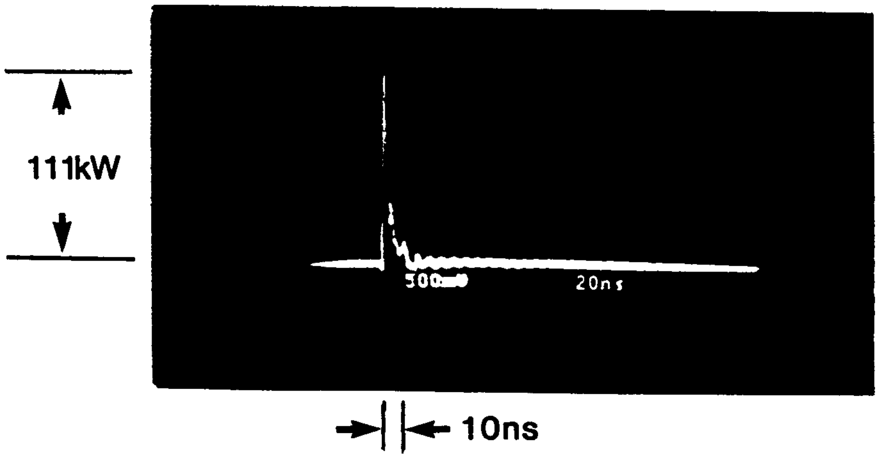

Figure 2 : 10ns amplified pulse of 111kW peak power (0.34mJ).

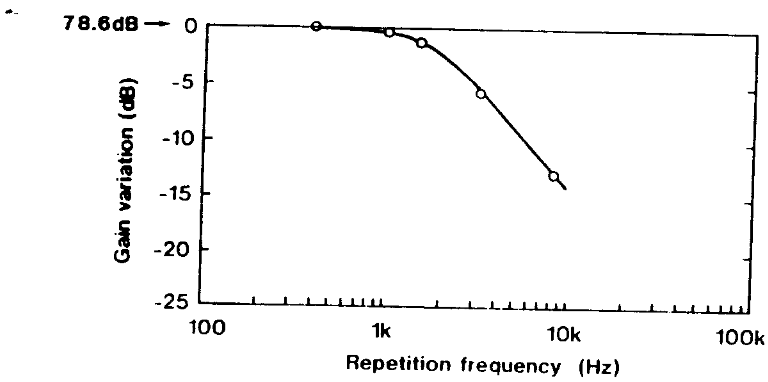

Figure 3 : Dependence of amplifier chain net gain on pulse repetition frequency. Here the input pulse width and peak power are 10ns and 1.53mW respectively whilst pump powers for EDFA 1/2 and 3 are HomW and 1.5W respectively.

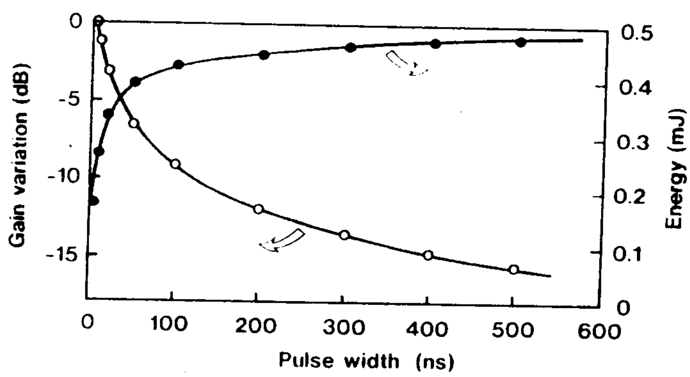

Figure 4 : Dependence of amplifier chain set gain and amplified pulse energy on input pulsewidth, here the input peak power is 1.53mW, the repetition frequency 400Hz and pump powers for EDFA 1/2 and 3 40mW and 1.5W respectively.

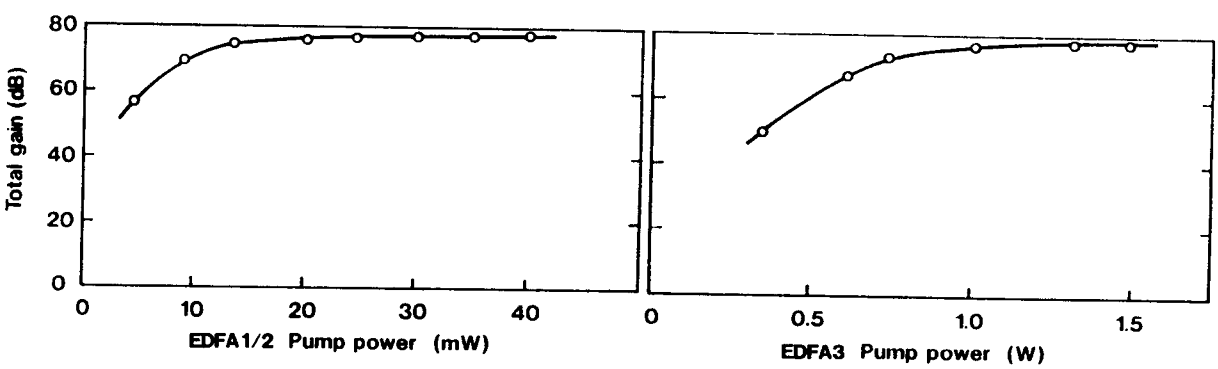

Figure 5 : Dependence of amplifier chain net gain on a) EDFA 1/2 pump power with EDFA3 pump power of 1.5W and b) EDFA3 pump power with EDFA 1/2 pump power of 40mW. In this case the input pulsewidth and peak power were 10ns and 1.53mW respectively and the repetition rate was 400Hz.