Large Mode Area Fibres for high power lasers

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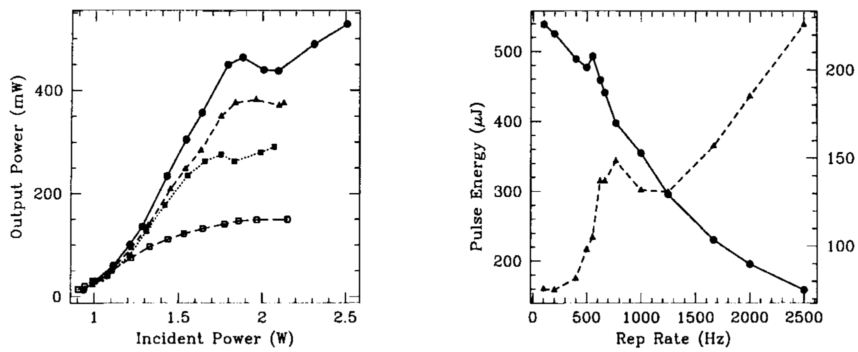
Fibre lasers are rapidly becoming increasingly attractive as high power versatile sources. We report here the development of large mode area erbium doped fibres. These fibres were then incorporated into simple laser cavities resulting in record pulse energy levels. Pulse energies as high as 512 μJ were obtained in a q-switched laser and in a passively mode-locked configuration near transformed limited femtosecond pulses with energies of 1 nJ were obtained.

1 Introduction

Fibre lasers are compact reliable sources for applications at eye-safe wavelengths around 1550 nm. For example fibre lasers are well suited to pumping nonlinear crystals such as periodically poled lithium niobate resulting in widely wavelength tunable sources[1]. Previously much of the work on erbium fibres has concentrated on maximising the small signal optical gain which requires a small spot size. However such small spot sizes increase the strength of nonlinear interaction and thus distort the signal at high powers. A simple way to reduce the nonlinearity is to increase mode area, while ideally insuring that the fibre remains single moded at the operating wavelength. Furthermore large mode areas also increase the energy storage in the fibre. Highly doped amplifier fibres with large mode areas have been fabricated which gave amplified pulses with energies $> 150\,\mu$J when used as the last stage of an amplifier cascade[2]. A second single mode, large mode area fibre with a mode field area of 310 μm which is nearly an order of magnitude greater than conventional fibre designs[3] was also fabricatd. This fibre was incorporated into a simple Q-switch configuration giving 180 μJ of pulse energy at a repetition rate of 200 Hz a record for fibre lasers.

Based on these earlier results we have designed and fabricated an improved fibre which an even greater mode field diameter. This fibre is a low NA multimode fibre with an additional raised index ring around the doped core and has a measured mode field diameter of 35 μm and a bend edge greater than 1600 nm. It was doped with 400ppm of erbium. Although, unfortunatly, the fibre was multimoded at the lasing wavelength (near 1560nm) it was found that it lased on a single transverse mode giving a high quality spatial beam profile. We incorporated this fibre into two simple lasers, a q-switched cavity and a passively mode-locked fibre lasers. In both cases the fibre gave excellent performance and the results are discussed below.



(a) Output Power Characteristics

(b) Pulse Energy

Figure 2: (a): Laser average output power characteristics. Solid circles – CW, triangles – 4kHz, solid squares – 1kHz, hollow squares – 400Hz. (b) Pulse energy (solid line) and width (dashed line) as a function of the repetition rate.

2 The Q-switched Fibre Laser

The experimental setup is shown in Fig. 1. For the Q-switched configuration the waveplates and the polariser were removed. The laser cavity was formed between the high reflection mirror (M2) at one end and the four percent Fresnel reflection from the cleaved output end of the fibre. The dichroic mirror was used to separate the pump and lasing wavelengths at the output. The acousto-optic modulator (AOM) was aligned for pulsing on the first order diffracted spot. The laser was pumped with a Ti-Sapphire laser delivering a maximum of 2.5 W at 980 nm of which approximately 60% was coupled into the fibre.

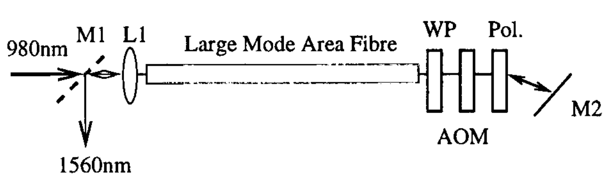


Figure 1: Schematic of the laser design. WP: $\lambda/2$ and $\lambda/4$ waveplates.

It was found that by varying the fibre length it was possible to optimise either the average output power or the output pulse energy. It was found that a fibre length of 8 m maximised the average output power and the output power characteristics of this laser is shown in Fig. 2(a) for a variety of repetition rates. Note that we acheived a maximum CW output power of 530 mW and that the average output power greater than 500 mW was obtainable under q-switched operation for repetition rates greater than 3 kHz. From the slope of the curve in Fig. 2(a) we estimate the quantum efficiency of the laser to be approximately 70% with respect to the launched power indicating that the fibre design is highly efficient. The threshold for operation was found to be approximately 900 mW of incident pump power. As mentioned previously it was found that despite the fibre being multimoded it lased on a single transverse mode with a mode field diameter of 35 μm.

Next the length of fibre was optimised for maximum pulse energy output, increasing the length from 8 m to 12 m. With this new length of fibre pulse energies in excess of 500 μJ were obtain at repetition rates below 400 Hz. The corresponding pulse width was approximately 70 ns. These results are shown in Fig. 2(b). These pulse energies are we believe a record for an active fibre system. The wavelength of operation was 1560 nm and had a bandwidth of $\approx$ 10 nm. The pulse spectrum could be cleaned up by inserting a narrow bandpass filter in the cavity. This reduced the spectrum to less than 0.5 nm and reduced the pulse energy to $\approx$ 250 μJ – which is still significantly more than has been previously reported.

3 Passively Mode-Locked Operation

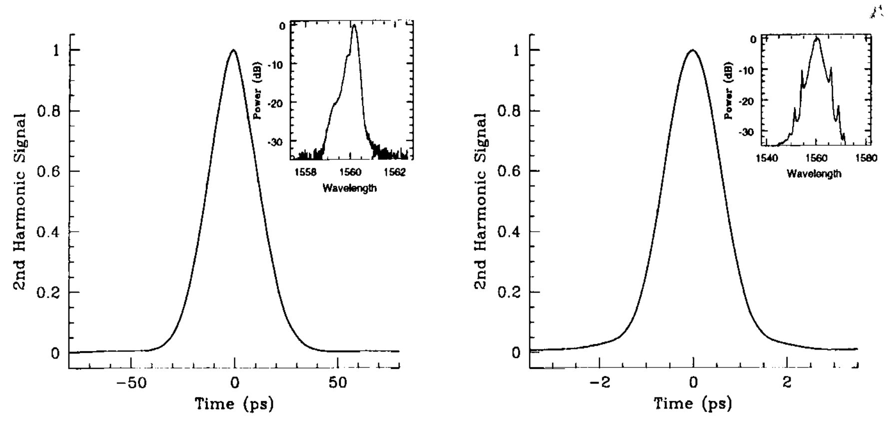
An advantage of operating the AOM in first order is that in this configuration it is possible to passively modelock the laser to produce short pulses. The basis of the modelocking is the interplay between the frequency shift caused by the AOM and the nonuniform gain profile[4, 5]. In the linear regime light is constantly downshifted until it eventually lies outside the gain bandwidth of the erbium and hence dies away. However in the nonlinear regime pulses can generate enough new frequencies via self phase modulation so as to always lie near the centre of the gain peak.

The laser was able to operate in two distinct mode-lock regimes depending on the polarisation control within the cavity[5]. Without the polariser (i.e. as a simple frequency shift laser) high energy (up to 20nJ), 20ps chirped square pulses were generated, this pulse energy is probably the highest ever reported from a mode-locked fibre laser cavity. The pulse's autocorrelation and spectrum is shown in Fig. 3(a). In the second distinct regime, i.e. with the waveplates and polariser in the cavity, the output pulses were near transformed limited 900 fs 1nJ soliton pulses with a estimated soliton order of 1.24 at the output (see Fig. 3(b)). From the sidelobes in the soliton's spectra we estimate the fibre dispersion to be 20 ps/nm/km. These pulses had a minimum repetition rate of 10.6 MHz corresponding to the cavity roundtrip time. For comparison note that the fundamental soliton energy in a convential fibre with the same dispersion is $\approx$ 20 pJ indicating the increase in pulse energy made possible by the increased mode area and hence reduced nonlinearity.

4 Conclusions

Using a large mode area fibre in a q-switched configuration we have obtained pulse energies of $> 500\,\mu$J at repetition rates less than $400Hz$. These energies are we believe the highest recorded for a fibre laser. The correspond peak powers are in excess of 5 kW suggesting that the source is suited to applications involving nonlinear frequency conversion.

In addition we have reported the first demonstration of passive mode-locking for a large mode area fibre. Using a simple cavity design we obtained femtosecond pulses with energies of $\approx$ 1 nJ. This demonstrates the scaling between mode size and energy which is to be expected in such lasers. Further improvements in the pulse energy should be obtainable with different cavity designs.



(a) Square pulse profile and spectra

(b) Femtosecond pulse output

Figure 3: Pulse autocorrelation and spectra for both the long square pulses (on the left) and the short femtosecond pulses (on the right). The pulse width for the short pulse is 900fs.

References

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