DEVELOPMENT OF A PHOTONIC CRYSTAL FIBRE LASER AMPLIFIER FOR PARTICLE BEAM DIAGNOSTICS

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Abstract

We present the latest results on the development of a high power fibre laser system for an ILC-specification laser-wire project. The laser consists of a crystal oscillator with wavelength ~ 1 µm that can be synchronised to an external frequency reference followed by chirped pulse amplification in ytterbium doped double clad fibre and photonic crystal fibre. This system produces 1 µJ pulses in an adjustable burst envelope at a chosen frequency. These pulses are further amplified in a large mode area rod-type photonic crystal fibre, allowing amplification to high pulse energies whilst maintaining a single spatial mode. The fibre is pumped in pulsed mode by a specially commissioned 400 W diode laser fixed at the absorption peak of ytterbium at 976 nm, independent of pumping regime. Pumping in a pulsed mode allows the high energies required for laser-wire at MHz repetition rates to be created without the need for active cooling of the laser. The light will be frequency doubled to ~ 500 nm to achieve improved laser-wire resolution.

INTRODUCTION

A laser-wire is a non-invasive particle beam profile measurement system that uses a high power laser focussed to a small spot to scan across a particle beam. Inverse-Compton scattered photons proportional to the overlap of the laser and particle beam are measured further along the accelerator giving the particle beam profile [1-3]. This paper focuses on the development of a high power fibre based laser system for this purpose. A summary of the requirements for a system suitable for a laser-wire are shown in Tab. 1.

Table 1: Required Laser Parameters

Parameter	Value
Repetition Rate	6.49 MHz
Pulse Energy	50 - 100 µJ
Pulse Duration	~ 1ps
Beam Quality	$M^2 < 1.1$
Wavelength	~ 500 nm

Whilst pulse energies of 100 µJ at 6.49 MHz are beyond current fibre laser technology, the system will be operated in a 1ms burst at 5 Hz. This reduces the average power required to within current technology, although this has not yet been demonstrated.

EXPERIMENT

A test system was built to investigate fibre amplification as shown in Fig. 1. Experiments were conducted using standard step index double clad single and multimode fibres as well as a large mode area rod-type photonic crystal fibre.

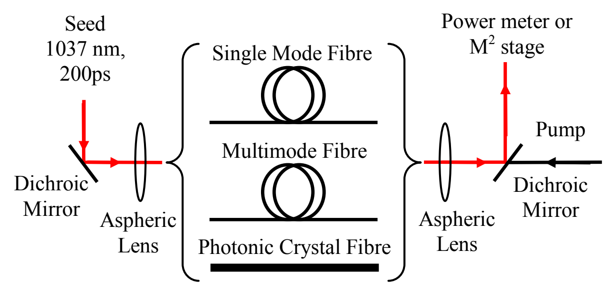

Figure 1 : Experimental setup.

The laser output from a commercial CPA system (Amplitude Systèmes, Bordeaux) [4] was coupled into the core of each fibre from one end and the pump into the inner cladding, in both cases using aspheric coupling lenses. The seed and pump beams were separated using dichroic mirrors with high reflectivity at 1037 nm and high transmission at the pump wavelength of 976 nm.

As shown in Tab. 1, a requirement is that the M^2 parameter (beam quality) be < 1.1 and ideally as close to 1 (theoretically perfect) as possible. The M^2 parameter is the ratio of the measured laser beam to that of a Gaussian. For this measurement a 2 m single mode fibre (6.5 µm diameter core) was used. This only supports the lowest order mode which, in a cylindrical waveguide, is a Bessel function and can be well approximated by a Gaussian [5]. To measure the M^2 of the system, the laser output of the fibre was focussed using a 300 mm lens with an iris placed directly before the lens. This ensures a minimal amount of background from any seed light not coupled into the core but carried in the surrounding inner cladding.

A CCD camera was used to measure transverse intensity profiles at various z positions through the focal region of the laser beam as shown in Fig. 2. The diameter at 4σ was measured 64 times and the average and corresponding z position plotted. This graph was then fitted to give the M^2 value of the laser beam. The experiment was repeated at different levels of amplification.

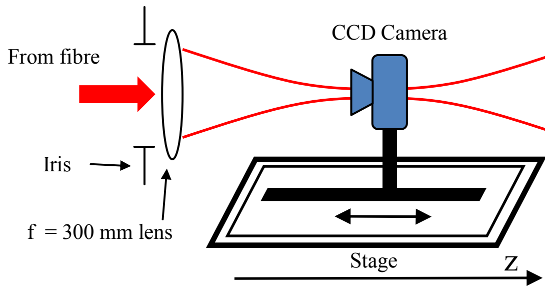

Figure 2: M^2 measurement system.

To investigate amplification in a burst regime as required for the final system, the same system was used but with a 2.7 m multimode fibre (15 µm diameter core). Both the seed and the pump laser were modulated by an external voltage from a Stanford Research Systems digital delay generator which allowed precise control of each laser individually. The seed was modulated to give a 2 ms burst at 2 Hz. The pump was initially given the same modulation at the same time. The length of the pump burst was then gradually increased to a maximum of 3 ms such that it preceded the seed burst but finished at the same time as shown in Fig. 3. The upper state lifetime of the Ytterbium dopant in the fibre is 1 ms and so a pump burst preceding the seed by longer than this time would lead to significant spontaneous emission and no further gain in extracted energy. 1 ms was therefore chosen as a suitable length to vary the pump pulse over. The absorbed pump energy as well as the output burst energy was measured using a thermal energy detector.

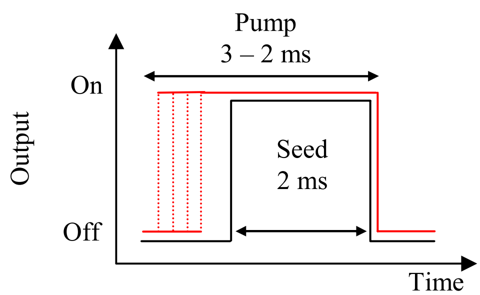

Figure 3: Burst temporal structure.

Continuous operation power measurements were taken using the same experimental setup and a 70 cm photonic crystal fibre with a 70 µm diameter core. This, unlike a conventional stepped refractive index fibre, utilises an array of microscopic air holes to create a structure that acts as a waveguide. This allows the fibre to be single mode even when the core diameter is large. The larger core area allows for higher levels of amplification and the avoidance of nonlinearities. Measurements of the output and absorbed pump power were taken for both the case of a fixed seed with a variable pump as well as a fixed pump and variable seed under quasi-continuous wave conditions.

RESULTS

Beam Quality

The input beam was measured in free space to have an M^2 of 1.09 ± 0.01 and 1.39 ± 0.01 in the horizontal and vertical planes respectively. The asymmetry in this output from a commercial system has been attributed to bypassing the optical compressor within it. The M^2 value of the fibre output in the horizontal and vertical planes as the level of amplification is increased is shown in Fig. 4. The M^2 values are plotted against the amplification factor which is the ratio of the output power to the input seed power. Fig. 4 demonstrates that the output beam quality is within the design criteria in Tab. 1 and that it does not degrade with amplification. Furthermore, the input has been significantly improved.

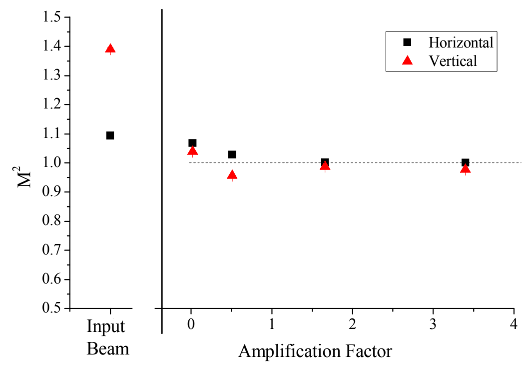

Figure 4: M^2 at various levels of amplification.

Burst Operation

The energy extracted from the amplifier per 2 ms seed burst at 2 Hz is shown in Fig. 5. This is the total energy output per burst with the unpumped output subtracted.

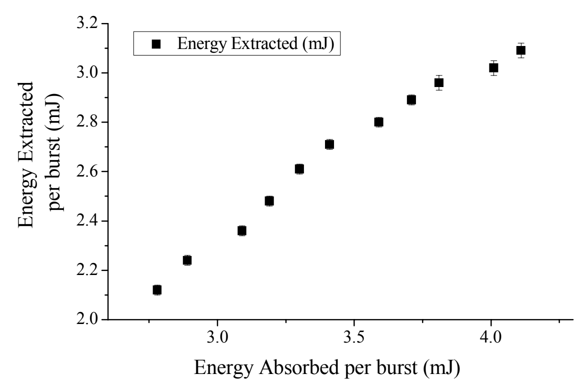

Figure 5: Extracted energy per 2ms seed burst.

As the pump burst was increased from 2 to 3 ms more energy was absorbed in the fibre. The energy absorbed was calculated by measuring the pump energy before and after the aspheric coupling lenses taking into account a measured 75 ± 1% coupling efficiency. Tests showed that the optimal lead time was 0.6 ms as this provided the greatest output without a significant proportion of the stored energy being extracted by the leading edge of the burst.

Figure 5 shows a maximum extraction efficiency of 79.5 ± 1.5% which is comparable to the 84% achieved under quasi-continuous wave conditions [6]. Energy is built up in the amplifier before being efficiently extracted to achieve a higher level of amplification than possible in a continuous regime.

Amplification in a PCF

The output power of the amplifier using the PCF as the pump power is increased is shown in Fig. 6. The slope efficiency found by the linear fit is 36.9 ± 0.1%. This can be compared to the manufacturer's performance guideline of 60% [7]. However, our experimental results are not corrected for pump coupling efficiency, which makes this result a lower limit of the achievable efficiency in this fibre.

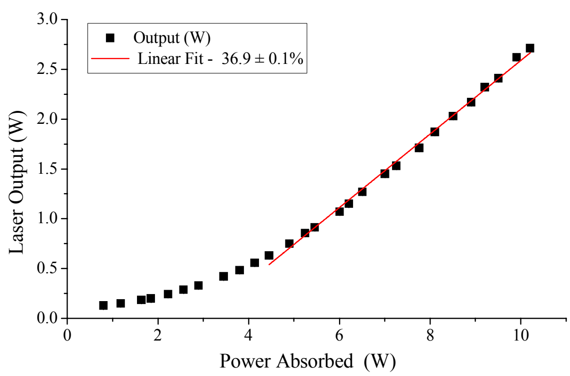

Figure 6: Output power of PCF amplifier.

Figure 7 shows the result of fixing the pump power at 10 W and varying the seed input power.

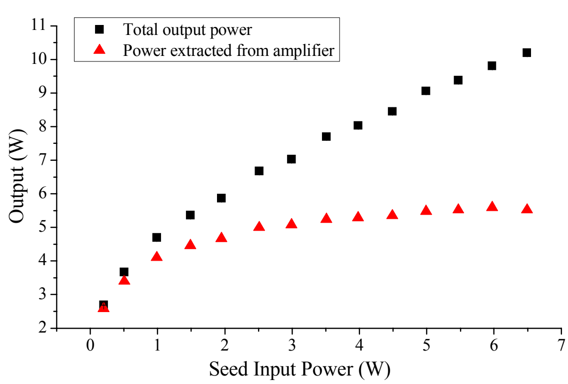

Figure 7: Output power with a variable input power.

As the input power increases the overall output also increases. However, the extracted power (total output minus unpumped output) approaches ~ 5.5 W representing the power stored in the amplifier at this given pump power. This is higher than the final required stored energy of 100 µJ pulses at 6.49 MHz for 1 ms at 5 Hz (~ 3.5 W) indicating the feasibility of the amplifier.

FUTURE WORK

More work is required to find the optimum temporal structure required to effectively extract the energy stored in the amplifier equally amongst all pulses in the 1ms burst. Further work is required to operate the PCF in a burst regime to fully demonstrate 100 µJ pulses required for a laser-wire. Additionally, an M^2 measurement of the output beam from the PCF should confirm the high quality expected. After this, an efficient optical compressor and frequency doubler will have to be constructed. The eventual aim is to install this system at the Accelerator Test Facility, KEK, Japan and demonstrate that it meets linear collider requirements.

CONCLUSION

We have demonstrated significant progress towards a fibre based laser system for a laser-wire. The experiments conducted show that we are able to achieve the necessary design criteria in both beam quality and energy stored in the amplifier.

REFERENCES

[1] P. Tenenbaum, T. Shintake 'Measurement of small electron-beam spots' *Annu. Rev. Nucl. Part. Sci.* **49**, 125 (1999).

[2] I. Agapov, G.A. Blair and M. Woodley, 'Beam emittance measurement with laser wire scanners in the International Linear Collider beam delivery system', *Phys. Rev. S.T. Accel. Beams* **10**, 112801 (2007).

[3] A. Bosco, M.T. Price, G.A. Blair, S.T. Boogert et al., 'A two-dimensional laser-wire scanner for electron accelerators' *Nucl. Instrum. Meth. A* **592**, 162 (2008).

[4] Y. Zaouter, E. Mottay, L. Corner and N. Delerue, 'Ultrafast amplified fiber laser for laser-wire measurements in particle accelerators', *Proc. SPIE* **6881**, 6881J (2008).

[5] G.P. Agrawal, Nonlinear Fiber Optics, 3rd Ed., Academic Press, San Diego (2001).

[6] L. Corner et al., ' Development of a high power fibre laser for laser based electron beam diagnostics' EPAC '08, Genoa, June 2008, TUPC124.

[7] Crystal Fibre, www.crystal-fibre.com/datasheets/DC-200-70-PM-Yb-rod.pdf (2009)