PHOTONIC CRYSTAL FIBRE LASER FOR ELECTRON BEAM EMITTANCE MEASUREMENT*

L. Corner, L.J. Nevay and R. Walczak, John Adams Institute at Oxford University, Keble Road, Oxford OX1 3RH, UK

Abstract

We present the successful development of a new fibre laser system for a laser-wire electron beam emittance diagnostic, suitable for intra-train scanning in an ILC-specification environment. The system is based on the amplification of a commercial Ytterbium (Yb) fibre laser with a repetition rate of 6.49MHz in rod type Yb doped photonic crystal fibre (PCF). We demonstrate world leading laser performance, with amplification of pulses from 1.5µJ to 268µJ and a beam quality factor $M^2 < 1.1$, in 1ms bursts at 2Hz.

INTRODUCTION

A laser-wire is a non-invasive method of measuring particle beam emittance. A high power laser is focussed to an extremely small spot size and scanned across a particle beam. The number of scattered photons (proportional to the overlap of the laser and particle beam) is measured further down the accelerator to give the particle distribution, which can be measured using this technique down to the micron level [1-3].

The specifications of a laser suitable for use in an ILC-like environment are shown in Tab. 1.

Table 1: Required Laser Parameters

Parameter	Value
Repetition rate	6.49MHz
Pulse energy	50 - 100µJ
Pulse duration	~ 1ps
Beam quality	$M^2 < 1.1$
Wavelength	~ 500nm

EXPERIMENT

To reach the energy required for a laser-wire experiment it is necessary to amplify the output of our commercial laser system. This is done in a rod type photonic crystal fibre, which supports high intensities without nonlinearities. The amplification of the seed pulses in the PCF is shown schematically in Fig. 1. The seed pulses from the commercial laser (Amplitude Systèmes, Bordeaux, 1µJ, 6.49MHz, 1037nm, 200ps) [4] are modulated using an EOM to produce bursts as short as 1ms (6490 pulses). The pulses are transmitted through an optical isolator which protects the seed laser from back reflections or lasing in the PCF, a λ/2 plate to correctly orient the laser polarisation with the axis of the polarisation maintaining PCF and then a series of lenses to couple the seed into the core of the fibre.

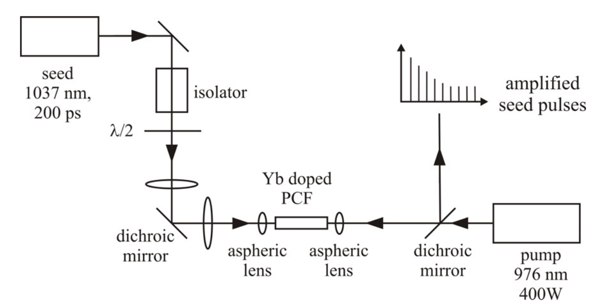

Figure 1: Experimental arrangement.

The 70cm long rod type PCF has a core diameter of 70µm, an inner cladding diameter of 200µm and an outer diameter of 1.7mm [5]. The seed is coupled into the core, which is doped with Yb, and the pump laser (400W, 976nm, Newport) is coupled into the inner cladding at the other end of the fibre. This counter-propagating geometry allows independent optimisation of the pump and seed coupling and efficient use of the pump energy. The seed and pump are separated by dichroic mirrors at either end of the fibre, which is made entirely of silica with no polymer coating, and is supported in a metal V groove. Due to the high efficiency of fibre lasers, the large surface area to volume ratio and the excellent thermal properties of the silica, the fibre requires no active or passive cooling and we have observed no damage to the fibre despite the high peak and average power output.

The core of the PCF is surrounded by a microscopic array of air holes which create a waveguide structure. This means that the core can have a large diameter while still remaining single spatial mode, which is important for preserving the beam quality of the seed after amplification. The large core area allows for high levels of amplification and the avoidance of nonlinearities. However, it also means the core has a very small numerical aperture (NA ~ 0.02), which requires careful alignment of the seed.

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To achieve the high single pass amplification required the fibre amplifier is operated in a burst mode [6]. Here the pump beam is turned on before the seed burst enters the amplifier, illustrated schematically in Fig. 2. Turning on the pump beam before the seed means significant upper state population (gain) is created in the amplifier which can be extracted by the seed pulses. The pump beam remains on during the seed amplification but there is not enough energy to replace the upper state population extracted by each seed pulse in the time between them (~155ns) and each pulse sees a smaller gain until the system reaches a steady state. This leads to an amplified burst train that exponentially decays in pulse energy to a steady state value. The seed burst extends slightly longer than the pump pulse to extract the gain remaining in the PCF after the pump is turned off.

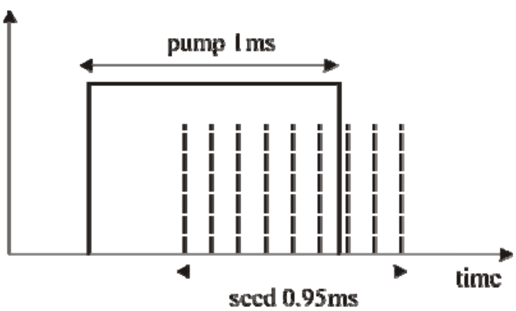

Figure 2: Burst temporal structure.

Experiments were carried out to find the optimum time delay between the pump and seed that maximised the amplified seed pulse energy i.e. before significant parasitic reduction in the gain by amplified spontaneous emission (ASE) in the fibre. The beam quality (M^2) of the output was measured and the spectrum of the amplified seed compared with the input to monitor whether any significant nonlinearities that would contribute to spectral broadening are introduced by amplification in the PCF.

RESULTS

The amplified seed pulse train is shown in Fig. 3.

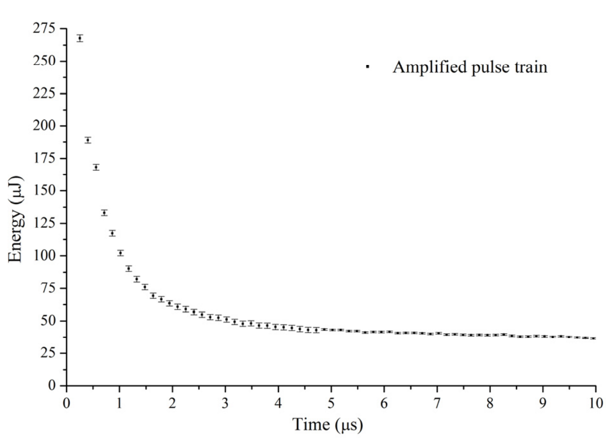

Figure 3: Amplified seed train.

The decay from the first pulse, which sees the highest gain in the fibre amplifier, to the steady state is clear. This data was taken using a 1ms long pump and a 0.95ms seed burst with a 0.2ms delay between the pump and seed. The total pump burst energy incident on the PCF was 313 ± 1mJ and the total seed burst energy was 9.34 ± 0.02mJ (i.e. an input pulse energy of 1.52μJ). The total energy of the output amplified pulses was 177 ± 1mJ.

The energy of the first pulse in the amplified train is 268μJ and the first six pulses in the train are > 100μJ, the pulse energy required in the original specification. This gives us the ability to perform intra-train scanning and significantly decrease the time required for a laser wire scan. The single pass gain for the first pulse is 32dB/m, an extremely high gain for this (or any) type of fibre laser.

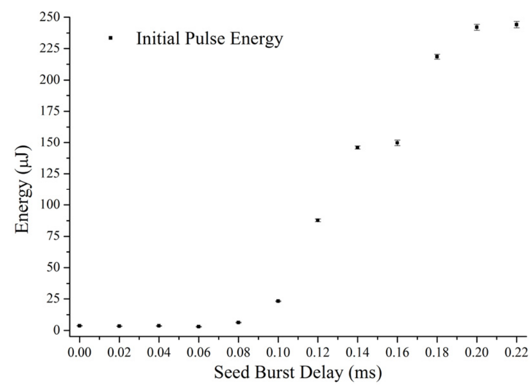

Figure 4: Energy of first amplified pulse as a function of the delay between pump and seed bursts.

The increase in the energy of the first pulse as a function of the delay of the seed burst after the pump is shown in Fig. 4. This clearly shows that it takes nearly 0.1ms of delay for there to be an appreciable gain built up in the amplifier, mostly due to the non-instantaneous rise time of the pump diode after it is turned on. For delays > 0.3ms, the energy of the first pulse decreases as the gain built up in the amplifier is reduced by ASE (observable in the spectra of the output at these delays).

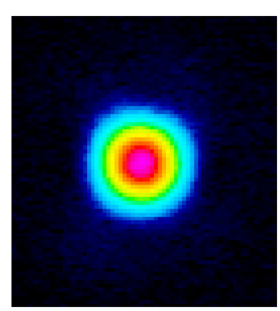

Figure 5: Amplified output at focus.

Figure 5 shows the amplified output beam at its focus, demonstrating the excellent spatial mode obtainable in the photonic crystal fibre. We measured the M^2 of the output to determine the beam quality and the results are shown in

Figs. 6a and 6b. These graphs show $M_x^2 = 1.07 \pm 0.02$ and $M_y^2 = 1.09 \pm 0.02$, which we believe are the best results reported in rod type PCF. This measurement also shows that the rod acts as an excellent spatial filter, as the M^2 of the input seed laser is ~ 1.6 in both dimensions.

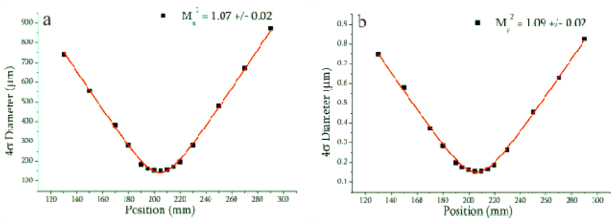

Figure 6: a) M_x^2 and b) M_y^2 of PCF output.

We observe no distortion of the spectrum of the amplified seed, indicating no significant nonlinearities or ASE are present in the output beam. This is shown in Figs. 7 and 8, which show the spectrum of the seed after the PCF at low pump level and with maximum pump energy, and the spectra of the seed zero delay and 0.22ms after the pump burst (giving maximum amplified output energy).

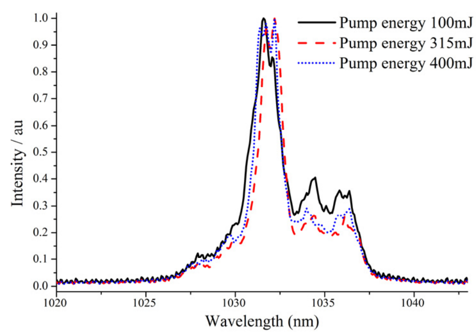

Figure 7: Amplified seed spectra for low, high and maximum pumping.

The lack of distortion of the amplified output indicates it should be possible to compress the pulses back to the initial nearly transform limited duration of the seed, < 1ps. Experiments on the output of the PCF at low amplification have shown it is possible to achieve a compressed pulse of σ = 1.5ps. The problem at higher energies is that the pulses may damage the fused silica gratings used for pulse compression, so work is continuing on optimising the beam size on the gratings to avoid any damage.

FUTURE WORK

Currently the amplified seed pulses are ~200ps long. Future work will concentrate on recompressing the pulses to 1 – 10ps and frequency doubling them to 519nm.

It is hoped that the system can be installed at the current laser-wire experiment on the ATF2 at KEK with the aim of achieving sub-micron resolution scans on several electron bunches in a train, significantly decreasing the time required to make a full measurement.

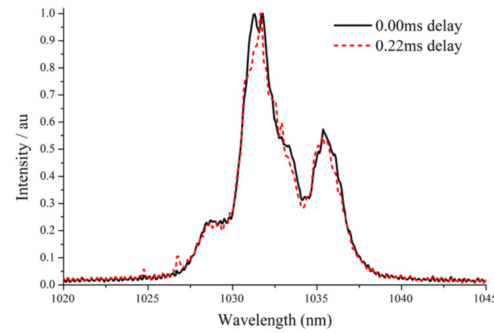

Figure 8: Amplified seed spectra for different delays between pump and seed bursts.

CONCLUSION

We have reported the near completion of an innovative high power fibre laser system for use in a laser-wire diagnostic. The high output energy and excellent beam quality means this system could be suitable for many other applications in accelerator science.

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