Progress Towards Coherent Combination of Free-Space Femtosecond Laser Pulses

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Introduction

The HAPPIE lab (**H**igh **A**verage and **P**eak **P**ower lasers for **I**nteraction **E**xperiments) was established as part of a Laserlab-Europe joint research agreement. It has continued operating under this name, working towards the coherent combination of free space femtosecond regime laser pulses. This report outlines the progress made during the past year, principally regarding temporal stabilisation

Coherent beam combining is of particular interest when considering methods of delivering higher peak intensities, as the intensity scales quadratically with the number of beams combined. The majority of research in this area has focussed on fibre sources [1]. This report discusses the techniques used to achieve free-space coherent combination and the robustness of the system when exposed to perturbations.

Setup

The optical setup consists of a single optical table, housing a frequency stabilised CW diode laser at 808 nm and a pulsed, 1053 nm Ti:Sapphire oscillator (Spectra-Physics 'Tsunami') operating at 1053 nm with a repetition rate of 80 MHz. The two lasers are spatially overlapped and propagated co-linearly through the system. The beam is first expanded to 10 mm square using two collimating telescopes and a square apodiser. A 50:50 beamsplitter divides the beam into two separate arms, each with a mirror mounted on a fast piezoelectric motion stage (piezo mirror - PM). A block diagram of this setup is shown in Figure 1.The PM mounts are designed so that any vibrations transferred from the mirror to the table or vice versa are damped. This is achieved using Sorbothane rubber feet with appropriate mass loading [2].

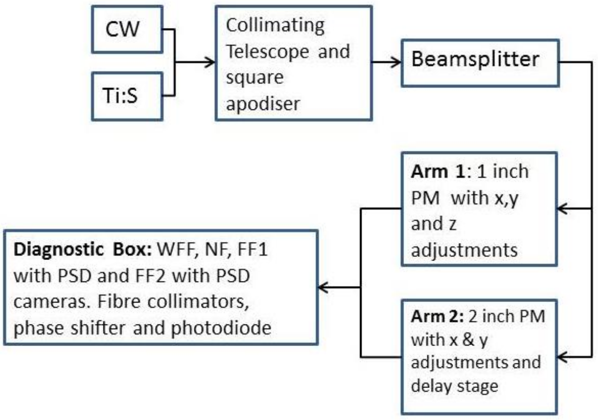

Figure 1: Block diagram of the beam path in the HAPPIE lab, showing the key components and the two laser sources in use.

The diagnostic suite (Figure 2) is contained in a box for environmental isolation. It comprises near and far-field cameras, position sensitive detectors (PSDs), and a balanced photodiode at the output of a fibre interferometer. A short-pass spectral filter is used to select only the 800 nm CW laser to send to the PSD/FF camera assemblies and fibre interferometer. The PSDs and photodiode provide the inputs to PID control modules that drive the PMs and a phase shifter.

Spatial Stabilisation

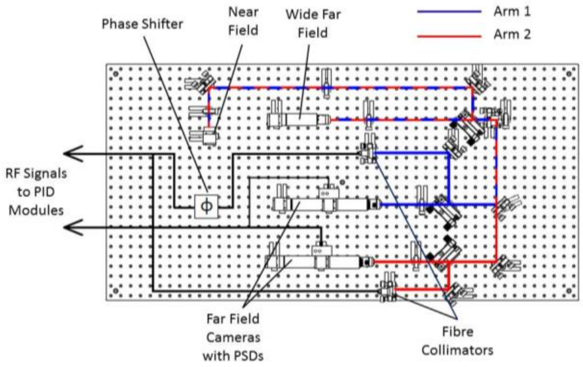

Figure 2: Layout of the diagnostics.

Previous work conducted in the HAPPIE lab succeeded in spatially locking the CW [2] and pulsed [3] beams in the far field (FF). The two PMs in the system are driven by PID control modules that regulate the beam position in x and y. The control modules obtain signals from the PSDs that capture the FF positions of each arm.

The two FFs were aligned to a reference which was then assigned to be the setpoint. The PSD output is fed into a Butterworth filter, and hence to the PID module which acts to correct deviations from the setpoint by driving the PMs in a suitable manner.

Altogether there are five parameters that are user inputted; filter frequency, filter order, proportional gain k_p, integral gain k_i and derivative gain k_d. To obtain appropriate values for these parameters, the setpoint is driven over a range of frequencies in order to characterise the mirror response. The Fourier transform of control output, u, of the PID module has the following equation [3]:

$$\boldsymbol{u(\omega) = k_p e(\omega)\left(1 - \frac{ik_i}{\omega} + k_d i\omega\right)} \tag{1}$$

e represents the error and ω angular frequency of the driven mirror. To find optimum stable parameter values Monte Carlo simulation is used to obtain desired numerical results, maximising attenuation at a particular frequency of interest or across a broader range.

Manipulating data from an initial slow scan using equation 1 and a Butterworth filter response generates a simulated response curve. The initial slow scan uses predefined parameters that don't act to stabilise the beam, instead it allows a voltage to be applied to the mirror and sees how the beam moves when driven at different frequencies. From this simulation response curve, stable closed loop parameters are generated and can be inputted into the PID modules.

Temporal Stabilisation

Before attempting to temporally lock the beams the entire optical setup must have a path difference (PD) of zero. The precision required for the delay stage is set by the coherence length of the pulsed laser, calculated to be 41±6 µm. Within this range interference between the two arms is visible on the WFF diagnostic, with highest contrast fringes corresponding to the best temporal overlap. Following layout modifications, the technique described in [3] was used to re-time the two arms. Initially a fast InGaAs photodiode and 7 GHz bandwidth oscilloscope were used for coarse timing, then spectral interferometry to reach minimum PD. Figure 3 shows the last stage of this process, ending with interference fringes visible in the far-field.

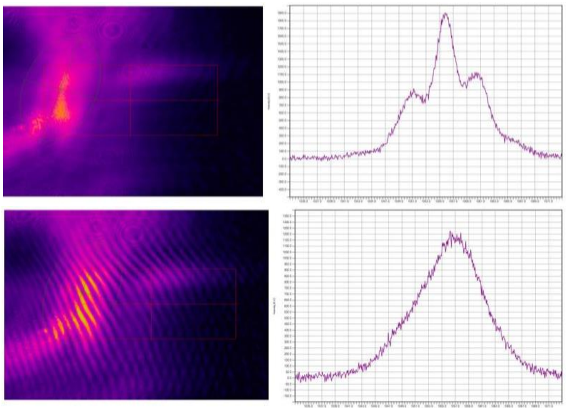

Figure 3: The top images show the focal spots and spectrum of the short pulses with a path difference of ~100 µm between the two arms. The bottom images are with the PD minimised; interference fringes are observed in the WFF diagnostic.

The temporal phase is measured by directing each arm into a fibre collimator attached to the input of a 50:50 ratio, 2x2 fibre coupler. This forms the end of a Mach-Zehnder interferometer, with one of the outputs directed to a photodiode (Thorlabs PDB410A) (Figure 4). The RF signal produced is dependent on the phase difference between the two beam paths. It has the following sinusoidal expression with the phase, φ, and delay, D, between the two fibre arms, given by equation 2:

$$\boldsymbol{RF\ (t) = Asin\left(\frac{2\pi}{\lambda}D(t) + \varphi(t)\right)} \qquad (2)$$

The response of the PM in z is insufficiently fast to keep pace with the phase change resulting from environmental influences. The magnitude of the change can be >π radians over the response time of the piezo driven mirror, resulting in a change of the sign in the response and making the loop unstable.

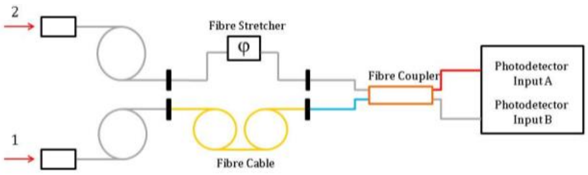

Figure 4: Fibre interferometer used to detect the phase shift between the two arms.

In order to maintain a linear response, a phase shifter (Optiphase PZ1) was introduced to one arm of the fibre coupler.

The phase shifter consists of a fibre wrapped around a piezoelectric element, small expansions of the piezo stretches the fibre, lengthening the optical path. The model is capable of operating at up to 40 kHz, and providing >100 µm additional path length, so is able to correct the sort of variations experienced in the lab with no difficulty. The applied voltage required to equalise the path lengths is linear, rather than the sinusoidal variation of the interferometer RF output. This can then be used as the input for the PID loop controlling the mirror Z position.

PID control cannot stabilise a sinusoidal response over a large value for D, however if the value for the delay was small, by adjusting the PD, the response would be approximately linear.

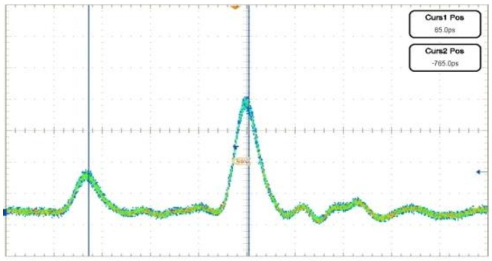

Figure 5: Oscilloscope trace of a Ti:S pulse separated in time due to the path difference between the fibre collimators.

The same technique of spectral interferometry was used to time the two diagnostic arms. Figure 5 illustrates a delay between the two pulses at the fibre collimators of 830ps, this equates to a PD of 0.17m. By introducing 0.17m of fibre cable to the early arm fine adjustments can be made to make the PD close to zero. A delay stage attached to a fibre collimator was used to make these fine adjustment, a spectrometer was used in this process.

The CW laser is then directed through the optical setup and into the fibre collimators. Adjusting the lens within the fibre collimators the RF signal that emerges from the photodetector can be optimised and balanced between the two paths.

The phase shifter acts a lot faster than the PMs so it'll be driven at max 300 kHz for the initial slow scan with PID parameters higher than before. Once the phase shifter is tuned the z axis of the 1 inch PM will be manipulated to stabilise the timing, this uses a similar method to how the PMs are spatially tuned. The x and y PID modules were actively stabilising the beam whilst the phase shifter PID module was placed in the initial slow scan. Once the data of this scan was processed, using Monte Carlo simulation, and the closed loop parameters tested an additional PID module was used to drive a PM in the z axis. The left image on Figure 6 shows the RF signal when the two beams interfering with each other with no manipulation in phase. When implementing PID control the phase shifter acts to reduce the RF signal to zero as shown by the right image.

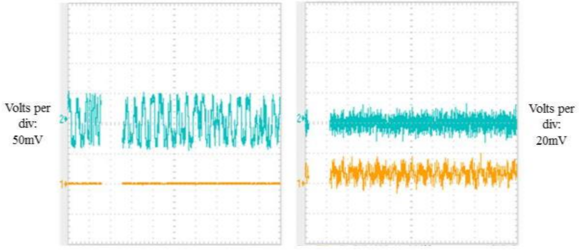

Figure 6: Oscilloscope traces showing the difference between temporal locking off and on. Channel 1 (yellow) is the signal from the phase shifter. Channel 2 (blue) is the RF signal from the photodiode. Left temporal locking is off. Right temporal locking is on.

The phase shifter is affected by external forces such as knocking on the table or the closing of a nearby door; tests to determine the robustness of the system are useful. A mirror in the setup can be made to shake, when set at 20Hz with amplitude of 2V the fringes on the WFF, with no PID running, were not distinguishable. However with PID running the system was able to stabilise and fringes were observed clearly.

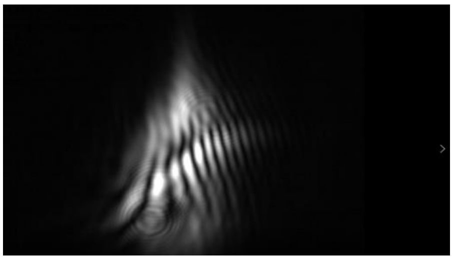

Figure 7: Wide Far Field Diagnostic with PID control activated.

Future Progress

The main constraint in the HAPPIE lab is the limited space, the footprint of the PMs, various diagnostics and the three PID units to combine two beams is big and expensive. Research and thought into solutions are ongoing for example new condensed diagnostics are being implemented; finding a way to utilise small single board computers like the Red Pitaya to replace PID units; and tests to determine whether a PM alone could temporal stabilise the beams would remove the need of expensive phase shifters. Next year the HAPPIE lab will progress towards a finessed version of the current system that will be researching techniques into beam combination of more than two beams.

Conclusions

The objective of this experiment was to achieve temporal locking of two beams, from a free space laser, as final steps of achieving coherent combination in the HAPPIE lab. This was achieved using PID control to drive both a phase shifter and a piezoelectrically adjustable mirror. With spatial and temporal PID control active the system was able to stabilise the two arms even when placed in an unstable environment. The next steps will be to expand upon the current system to achieve coherent combination of a number of beams.

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References

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