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Citation: [AIP Conference Proceedings](#) **1812**, 110002 (2017); doi: 10.1063/1.4975915

View online: <https://doi.org/10.1063/1.4975915>

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The Coherent Combination of Fibre Lasers – Towards Realistic Applications

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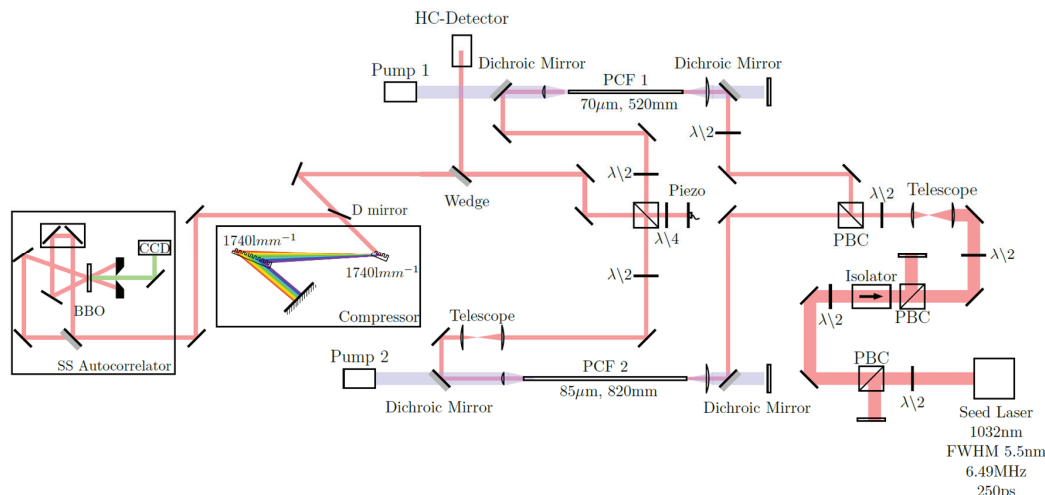
Abstract. To drive a laser-plasma wakefield, high peak-power laser pulses are required. For useful accelerator applications, it is also necessary to have driving lasers with high efficiency, repetition rates, and average power. The coherent combination of Ytterbium-doped fibre laser amplifiers is a promising potential solution, and previous work has demonstrated the successful combination of near-identical ultrafast fibre lasers. We report here the combination of significantly mismatched Ytterbium-doped photonic crystal fibre amplifiers with a combined efficiency of 96%, while the locked power output remained stable for 6 hours. The combined output of the system had a total gain of 12 dB, with no detrimental effect on the compressed pulse width observed.

INTRODUCTION

Fibre lasers are attractive candidates to drive laser-plasma wakefields, as they possess high wall-plug efficiencies (typically, two orders of magnitude larger than typical Ti:Sapphire laser systems used for high peak power pulses) and high average powers. However, in order to drive a wakefield, high peak powers (typically TW) are required. Previous theoretical work [1] has shown that the maximum peak power that can be extracted from a photonic crystal fibre (PCF) is of the order of 10 GW. So, to drive a wakefield, the output of many fibres need to be combined together [1, 2, 3]. A facility-scale, coherently-combined fibre-laser system, utilising potentially hundreds of PCFs, will generate significant cost. These costs are likely to increase, if stringent constraints on the fibres being near-identical for efficient combination are necessary.

One aspect of designing a facility-sized system is to identify where costs can be reduced by informed design choices. This includes identifying where tolerances can be relaxed, which could potentially reduce the cost of individual components. The tolerances we refer to here are those of the PCFs themselves, testing the limits of the requirement for identical fibres for successful combination by combining non-identical PCFs. Here, we demonstrate the successful coherent combination of two amplified PCFs in a Mach-Zehnder interferometer [4] stabilised using the Hänsch-Couillaud method [5]. The seed for the amplification and combination experiment was a 6.49 MHz pulsed Yb-doped fibre laser at 1032 nm, with a stretched pulse duration of ~250 ps and a compressed pulse duration of ~430 fs. The output of this laser is then split equally at a polarising beam cube (PBC), and each beam is then used to seed a PCF. The PCFs are themselves significantly different, having different lengths (520 mm and 820 mm), different core sizes (70 μm and 85 μm), and different internal structures. In addition, the 70- μm core PCF contains polarisation-maintaining stress rods, while the 85- μm core PCF does not. The subsequent effect of using different core sizes, and the presence of protective end caps on one of the PCFs, means that the wavefronts from each PCF are very different at the point of combination.

COHERENT COMBINATION OF MISMATCHED PHOTONIC CRYSTAL FIBRES



A Mach-Zehnder interferometer is used to combine the mismatched PCFs together, stabilised with a piezo-mounted mirror whose longitudinal position can be locked using the Hänsch-Couillaud method. Simple 1D pulse propagation simulations show that the difference in material dispersion between the two PCFs has little impact on the phase difference between the two pulses and still allowed for good combination. Other theoretical work done [6], used a figure of merit to estimate the quality of combination between 2 pulses. The FOM uses both the difference in dispersive material travelled and B integral between 2 pulses. It is calculated separately for different bandwidths and produces a surface plot. Here, despite the differences in material dispersion and B integral, they also concluded that good combination should be possible. This is in part due to the relatively narrow 5.5-nm (FWHM) bandwidth of the seed, making it less sensitive to dispersive effects than a broader bandwidth pulse. The biggest obstacle to efficient beam combination is the differences between the wavefronts. The core size and beam path to the point of combination are different for each PCF, so resulted in each beam having a different beam size and divergence at the combination beam cube. This translates into each beam having a different radius of curvature when they combine (see Fig. 2). Simulations were performed on two beams with perfect spherical wavefronts, but with different radii of curvature, combining to give interference rings.

The locked system is characterised as having a combining efficiency of 96% with an average output power of 4.86 W. The combining efficiency is defined as [7]:

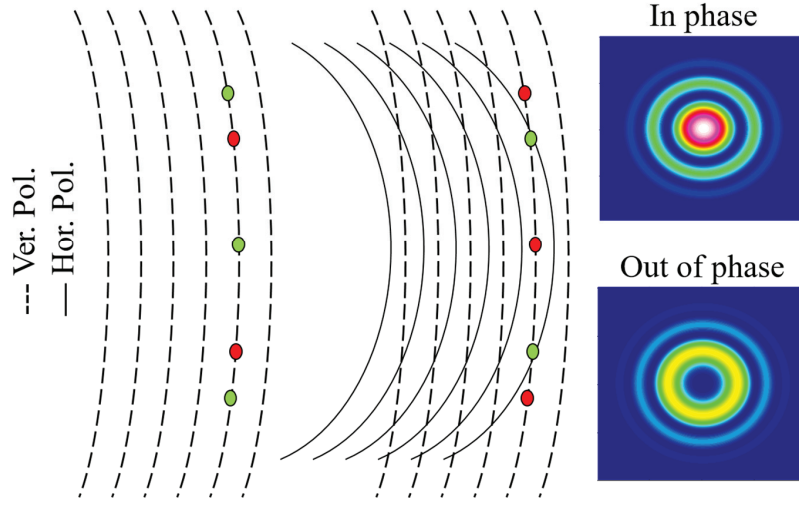


FIGURE 2. The beam profiles at the right show the simulation results of two perfectly spherical wavefronts with different radii of curvature combining to produce a beam with a polarisation state varying radially outwards. To the left is a 2D representation of the interaction of these wavefronts for illustration. Here, the solid line is a wavefront that is horizontally polarised, whilst the dashed line is a wavefront that is vertically polarised. The spots are places where the polarisation state is well defined as linear, with alternating spots representing orthogonal polarisation states with respect to each other. Everywhere in between the spots (following the dashed line) are varying degrees of elliptical polarisation. When the beams are displaced temporally, the beams shift from in phase to out of phase. This is observed as the interference rings growing or shrinking in size towards the centre.

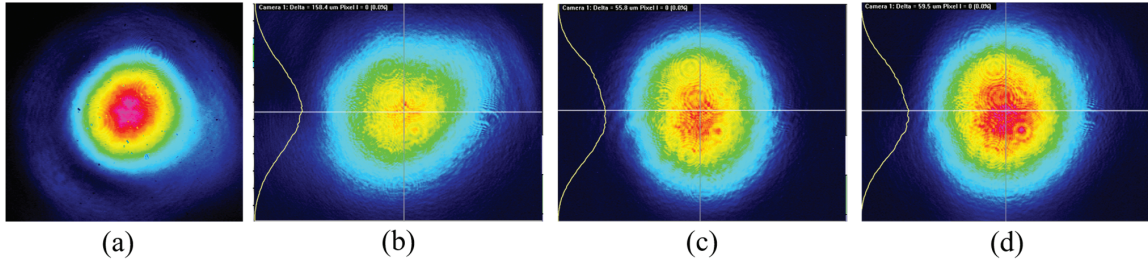


FIGURE 3. The beam profile as viewed through a polarising beam cube after the output of the system. A half-wave plate is used to change the polarisation state of the incident beam into the beam cube. This is due to the 70- μm and 85- μm PCF beam profiles having orthogonal polarisation states. (a) The combined beam of the 70- μm and 85- μm PCFs with mismatched wavefronts. (b) 70- μm beam profile. (c) 85- μm beam profile. (d) Combined beam profile.

$$\eta_{comb} = \frac{P_{comb}}{\sum_i P_i}, \quad (1)$$

where η_{comb} is the combining efficiency, P_{comb} is the locked combined output power of the system and P_i are the individual (unlocked) powers measured after the point of combination. However, for two channels, the system efficiency is a better metric for characterising the system, which is defined as per (1), except that the individual powers are measured immediately prior to the point of combination. This then accounts for the power losses due to imperfect combining elements and polarisation losses. Here, the system efficiency is measured to be 86%. Figure 4 shows the autocorrelation of the combined amplified beam overlaid with the seed beam. The compressor is initially tuned for

the seed laser and then readjusted for the amplified beam. Only minor adjustment is required, and the amplified pulse compression is as good as the best unamplified pulse compression.

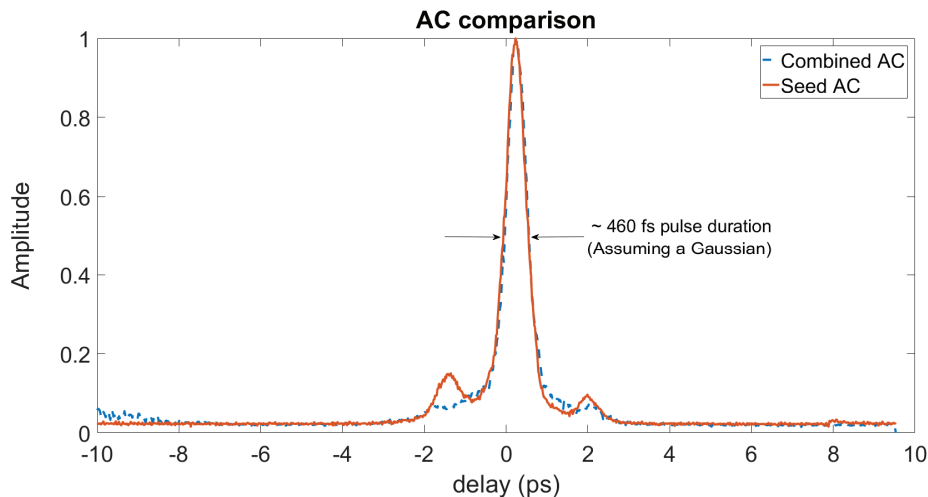


FIGURE 4. The autocorrelations of the seed and amplified beams.

The pulse energy from this system, given the average output power and a repetition rate of 6.49 MHz, is calculated to be ~ 747 nJ before compression. Calculating the central pulse (assuming a Gaussian profile) to contain 75% of the pulse energy, the compressed pulse gives a theoretical peak power of 1 MW before compressor efficiencies are accounted for. This system is running at a total gain of 12 dB, with the 70- μm and 85- μm PCFs having gains of 11.6 dB and 12.4 dB, respectively. The degree of linear polarisation of the system output was characterised to be 83%. These results make up a low power test of the setup; higher power tests are planned in the near future. In these, we expect to be able to reach higher peak powers.

CONCLUSION AND OUTLOOK

This is the first time, to the best of our knowledge, that two significantly different PCF amplifiers have been successfully coherently combined. The system had a total output power of 4.86 W, which gives a theoretical peak power of 1 MW before compressor efficiencies are included. The system was characterised as having a gain of 12dB, a system efficiency of 86%, a degree of linear polarisation of 83%, and the locked power output was stable over the course of 6 hours. It is clear from the setup that it would be unwise to purposefully choose to have amplifiers with such different properties. However, this experiment shows that a coherent-combination setup is able to withstand significant mismatch between the amplifiers with a high degree of linear polarisation. In terms of its effect on an industrial scale system, from a manufacturer's perspective, this translates to reduced PCF tolerances in terms of length and core size. Whereas before, one could expect tolerances of $\pm \sim 0.5$ mm and $\pm \sim 1$ μm , respectively (for example), the tolerances could possibly be relaxed to $\pm \sim 5$ mm and $\pm \sim 2$ μm , respectively, or even further in terms of length. This would contribute towards a reduced wastage and cost per fibre, which could have a significant impact on the total cost of a combined system consisting of hundreds of fibres. The next steps to be taken from here are to increase the average output powers of each PCF in the current configuration, and then to increase the peak power by reducing the repetition rate of the system.

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